Social Organisation and the Rise of Civilisation in the Mun River Valley, Thailand

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Charlotte Louise King

Abstract

As one of the most extensively excavated and archaeologically interesting areas of Thailand, the Upper Mun River valley is central to archaeologists' interpretations of Southeast Asian prehistory. In this area there is demonstrable growth in social complexity from first occupation to eventual annexation by the state society of Angkor in the mid first millennium AD. The exact nature of social evolution, however, is still not fully understood. Debate rages over the factors upon which social stratification was based, whether hierarchy or heterarchy was in place, the timing of agricultural intensification and impact of external populations.

In this thesis isotopic studies are combined with osteological indicators of kinship and population affinity to shed light on these and other archaeological problems which remain unanswered in the Upper Mun River Valley. Isotopic analysis has allowed the identification of migrants in the cemetery of Ban Non Wat, and shown changes in subsistence strategy through time relating to the onset of social inequality and climate change. Analysis of cranial shape has shown that most migrant individuals have similar

genetic backgrounds to local people, but with the notable exception of one of the only adult jar burials at the site. The combination of dental non-metric techniques, isotopic analysis and cranial shape analysis has also added evidence to the debates over the presence of hunter-gatherers at the site, and the nature of social organization.

Social Organisation and the Rise of Civilisation in the Mun River Valley, Thailand

A multidisciplinary study

A thesis submitted in fulfillment of the requirements for the degree
of
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Manuscript 1

Abbreviations used in this thesis

Regional and Site abbreviations:

UMRV – Upper Mun River Valley

BNW – Ban Non Wat

NUL – Noen U-Loke

BLK – Ban Lum Khao

Scientific Abbreviations/formulae

N – Normal (with reference to acid composition), similar to concentration, refers roughly to the grams of acid per litre of the solution used.

HNO_3-Nitric Acid

HCl - Hydrochloric acid.

MC-ICP-MS – Multi collector inductively coupled plasma mass spectrometry

LA-ICP-MS – Laser ablation inductively coupled plasma mass spectrometry

TIMS – Thermal ionisation mass spectrometry

Morphometrics/Statistical testing abbreviations

GPA –General Procrustes Analysis

PCA – Principal Components Analysis

CVA – Canonical Variates Analysis

CV-DFA – Cross validated discriminant function analysis.

Declaration

This thesis is by publication, and its results presented in the form of manuscripts. All manuscripts have multiple authors, therefore to clarify which work within them is the author's own, and which parts have been contributed to by others table 1 (after Winston, 1985) is given below.

Contribution: x entirely own contribution, x major contribution with co-authors contributing, (x) minor contribution.

Activity	*Paper 1* -Social Organisation in the Prehistoric UMRV.	*Paper 2* - Mixed economies after the agricultural revolution in Southeast Asia?	*Paper 3* - Moving peoples, changing diets.	*Paper 4* - Isotopes and Osteology
Conceptualising and refining research ideas	x	x	x	x
Literature search	x	x	x	x
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Statistical test selection	x	x	x	(x)
Performing statistical analysis	x	x	x	(x)
Drawing figures	x	x	x	x
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Interpretation of statistical analysis	x	x	x	x
First draft of manuscript	x	x	x	x

Later drafts of manuscript	x	x	x	x
Editing manuscript	x	x	x	x

Table 1: List of my contribution to the four research articles constituting the results section of this thesis.

Statement of Copyright

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This thesis could not have been written without many people, and it seems only fair that they are thanked here.

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Thank you all so much.

1. Introduction

This thesis outlines the results of a comprehensive study into migration and community structure in the Upper Mun River Valley (UMRV) of Northeast Thailand during prehistory. The focus of the research is the growth in social complexity, and rise of the state in this region.

In order to understand the *origins* of the state, however, it is first necessary to understand what preceded it, and trace social evolution through the prehistoric settlements of the valley. In order to achieve this, comprehensive osteological and isotopic analysis of individuals from the cemetery of Ban Non Wat (BNW) was undertaken. Ban Non Wat is one of the largest and most comprehensively excavated sites in the Upper Mun River Valley. Its cemetery sample comprises over 650 individuals spanning an occupation period of over 2000 years. Study of this site, therefore, can give unique insight into ways of life and change over time in this important archaeological landscape.

1.1 Research questions:

There are many different factors which may influence social complexity in any given region. This study focuses on the possible impacts of migrant individuals, the connection of social changes to environmental change, and the level to which kinship groups and interactions across an archaeological landscape were important. In order to focus the research, the following questions were considered:

1.1a What (if any) impact did migrant individuals have on the rise of complex society?

Migration is an important process in prehistory, as it is now, as it has the power to shape the evolution of society (Burmeister, 2000; Anthony, 1997). Migration not only moves people, but also their ideas, technologies and culture across a landscape (Anthony, 1990, section 2.1). Changes in social structure in the archaeological record, therefore, are often ascribed to the influx of migrant groups. This is particularly true in early archaeological research, where the belief that 'superior' societies influenced 'savage' ones was common (e.g. Coédes, 1968; Kuper, 2005).

In Southeast Asia migration has been invoked as an explanation for the advent of both agriculture and metal-working (Higham, 2002; Bellwood, 2001). This process is therefore likely to have had at least some influence in the prehistoric period. Foreign cultures have also had an impact in the historic period in the form of annexation of the UMRV by the Angkorian Empire in 1100AD (section 5.3). Previous research in the UMRV, however, indicates that migrants were not prevalent in any period of the region's prehistory, but these studies have not involved large sample sizes.

This large-scale study of a single site should definitively show the presence/absence of migrants, and allow estimation of the extent of external influence on the rise of social complexity.

1.1b What was the nature of social differentiation during prehistory?

It seems obvious from discrepancies in mortuary wealth and the presence of items which could be considered prestige goods (Higham & Kijngam, 2009; 2012) in the later phases of prehistory, that there was some level of social differentiation in placein the UMRV. There has, however, been much debate as to the form this took. What was status differentiation based on? Was social order rigid or flexible? Central to this debate is whether or not status was based on kinship, and rank hereditary. This issue is detailed in section 3, and in this study isotopic analysis is combined with osteological indicators of kinship in an attempt to reveal which of the proposed scenarios is most likely.

1.1c Was the UMRV a culturally homogeneous whole in the past?

In the European Neolithic the introduction of agriculture results in aswift and complete change to subsistence strategy, social organization and material culture (Rowley-Conwy, 2011). In Southeast Asia, however, cultural diversity appears to have been more common (c.f. White, 2011), even beyond the advent of agriculture (section 5.5).

In comparing isotopic results from Ban Non Wat to those already obtained from other sites in the UMRV this research aims to evaluate whether there is variation in reliance on rice agriculture across the archaeological landscape. This will aid interpretation of interaction, and give insight into whether proposed cultural pluralism extends to diet and subsistence.

1.1d What, if any, impact did climate change have on past human subsistence strategy and social organisation?

There is a growing body of evidence which suggest dramatic climate change occurred over the course of Ban Non Wat's occupation (e.g. Boyd, 2008; Boyd & McGrath, 2001; Wang et al., 2005; Lückge, 2004). As a result of this many archaeologists working in the area now hypothesise that a transition to drier conditions in the Iron Age led to the construction of moats to conserve water (Boyd, 2008), and an increase in the ritual importance of rice due to the difficulties involved in growing it (Boyd & Chang, 2010).

Changes in environmental conditions are often closely linked to changes in social structure e.g. the Younger Dryas period is directly correlated to the origins of agriculture in Asia and therefore the transition to Neolithic society (Higham, 2002; section 4.3). The climate is therefore an important variable to consider when studying social complexity.

In analysing both carbon and oxygen isotope ratios from dental enamel carbonate this study obtained a record of climatic variation during enamel mineralisation which correlates directly with a dietary signal. Effectively this allowed tracing of subsistence change with climatic variation, and evaluation of the impact that this may have had on social structure.

1.2 Methodological concerns

In addition to these questions focusing on social change in the Upper Mun River Valley, this research also aimed to explore methodological issues on how migration and population affinities are recognised in the archaeological record. Specifically this study evaluates whether or not osteological indicators of population affinity such as cranial morphology and dental non-metric traits, may be used to identify migrant individuals as effectively as established isotopic techniques.

1.3 Structure of the thesis

This thesis by publication addresses three primary themes: the impact of migration on the rise of social complexity, the nature of social differentiation and interaction across the archaeological landscape, and the correlation of these social changes with environmental and subsistence changes. The introductory section of the thesis details the research questions and underlying archaeological issues which have been explored in the course of this study. The literature review (sections 2-4) which follows outlines studies relevant as background to this research; the techniques which have been used by others in addressing similar research questions and the theories which are commonly invoked to explain change.

The archaeological context of Southeast Asia in general, and the Upper Mun River valley in particular, is detailed in section 5, and materials and methods used to explore the research questions are given in sections 6 to 11. The results of this study are presented as a series of manuscripts submitted for publication (sections 12-16).

1.4 The publications and their relevance to the research focus

Results are broken down into four publications. The first three of these focus on isotopic results, and the information they yielded regarding social organisation, interaction and complexity. The last manuscript relates to the use of osteological techniques in identifying migration and kinship to gain a bigger picture of relationships within the BNW cemetery sample and interactions across an archaeological landscape.

Manuscript 1 –Social Organisation in the Prehistoric Mun River Valley: The story from the isotopes at Ban Non Wat.

This paper uses strontium isotope results to evaluate whether migrant individuals are present within Ban Non Wat, and offer interpretations regarding the organisation of society. Extremely low levels of long-distance migration were found in the site, making the development of social complexity likely to be intrinsic. Hypothetical isotopic result sets representing hierarchical and heterarchical social organization weredeveloped within this paper. The data was then tested with regard to these, to show that an inflexible social hierarchy is unlikely to have been present at Ban Non Wat.

Manuscript 2 – Mixed economies after the agricultural revolution in Southeast Asia?

This paper expands on the first, which looks only at results from Ban Non Wat, and compares dietary isotope results with those from the nearby sites of Noen U- Loke and Ban Lum Khao. This addresses the third research question of this study, looking at differences in diet to offer interpretations about interaction across the archaeological landscape. Significant dietary differences between the sites are found, based on level of reliance on C_3 crop food sources i.e. rice agriculture. It is proposed that these differences relate to the non-uniform uptake of agriculture, and cultural pluralism across the UMRV.

Manuscript 3 – Moving peoples, changing diets: Isotopic differences highlight migration and subsistence changes in the Upper Mun River Valley, Thailand.

This paper focuses on dietary isotope results to further shed light on the issue of migration in the Upper Mun River valley. The homogeneity of the underlying groundrock in the UMRV means that strontium isotope analysis cannot be relied upon to identify migrants. Carbon isotope analysis presented here shows that some individuals have evidence for C_4 or marine resource use, hinting that their origins may be external to the UMRV, despite a similar strontium isotope ratio. Correlations are made to unusual burial practice, hinting at a different status assignation for migrant individuals. This paper also examines sex-based differences in diet. Sex is often an important factor in status assignation, particularly in a hierarchical society. Study of dietary isotopes with regard to sex reveals differences in diet between them in the mortuary phases with the highest level of discrepancy in mortuary wealth between individuals.

Manuscript 4 –Isotopes and Osteology: Using the multi-disciplinary approach to establish population affinity at Ban Non Wat, Thailand.

The results of the pilot study presented in manuscript four indicated that application of geometric morphometric and other osteological techniques to the Ban Non Wat sample may help identify migrants. This study found carbon isotope outliers (i.e. those with differences in diet) were most readily identifiable using osteological techniques, whilst long-distance migrants (Sr isotope outliers) were effectively invisible osteologically. It therefore appears that genetic admixture, even between geographically distant populations, was common in prehistory, making biological differences between migrants and local individuals minimal.

This study also used chi-square testing to identify ‘morphological migrants’, finding interesting correlations between those with unusual burial practice and dental non-metric trait occurrence.

2. The Study of Migration

"Migration is a structured and well-studied aspect of human behavior. Archaeologists, however, generally treat migration as chaotic and poorly understood."

- Anthony, 1990 (pp. 895)

2.1 The study of migration and population movement in archaeology

Migration in the context of human society refers to systematic movement of people from one area to another. It is generally agreed that migrant groups can quite seriously affect cultural evolution in an area (Anthony, 1990), yet the problems of differentiating migration from diffusion or trade in the material record mean that it is often not addressed as a topic (Burmeister, 2000). Migration studies are fraught with difficulty as they centre on the ability of the archaeologist to define 'ethnicity' (Anthony, 1990; Burmeister, 2000; Frankel, 2003), and only by establishing significant differences between indigenous and settler cultures can an argument for population movement be made (Frankel, 2000).

Early attempts to identify ethnic groups focused on the establishment of 'cultural groups' and tracing movement of the material culture associated with them across the archaeological landscape (Rouse, 1986; Croucher & Wynne-Jones, 2006). This idea was introduced by Graebner (1911), and notably both used by Kossinato trace the migration of 'barbarian culture' across the Roman Empire (Musset & James, 1975), and abused by the Nazi party to support the idea of Aryan supremacy in the mid-20th century (Arnold, 1990).

The idea of culture complexes representing migrant groups was refined by Childe (1958), and became the accepted wisdom in archaeology.

Use of material culture to trace migration events does still occur today. The technique has been applied in the Black sea region to show movement of farming people across the landscape (Sheratt, 1981; Anthony, 1990), used by Frankel (2000) to explain cultural and technological change at the onset of the Bronze Age in Cyprus, and Naum (2012) to highlight the influx of Slavic migrants to Denmark. Hybrid ceramic forms have also been used to understand the power-plays at work during colonial expansion into New Mexico (Mills, 2008), and Trigger (1976) also suggests that the presence/absence of foreign pottery in sites may be considered an index of female movement among the Iroquoian people.

Most studies, however, have moved away from this material culture approach to defining migration. It is recognized that only in very clear cut instances, for instance colonization of previously uninhabited Polynesia by the Lapita people (Spriggs, 1984; Anthony, 1990), can material culture be considered definitive evidence of population movement. Material culture continuity may be due not only to the movement of people, but also cultural diffusion and trade (Burmeister, 2000; Trigger, 1968). In addition to this there is the problem that migrant people are not always part of a single cohesive culture group, as has been shown for the Germanic migrations of 500-600AD (Knipper et al., 2012). There is also no reason to assume a group of people will leave their homeland and set-up elsewhere using exactly the same social structure, material culture and way of life (Burmeister, 2000).

Even if cultural complexes do represent population movement it is difficult to equate artifact distributions with thought processes, or the complex interactions between parent communities and their offspring. There is rarely one-way traffic during a migration event, the scale of migration may be small or large, the reasons for migration multi-factorial, and the impact of migrants disproportionate to their material remains. The complexity of migration has been explored by Anthony (1990) and is given graphically on figure 2.1.

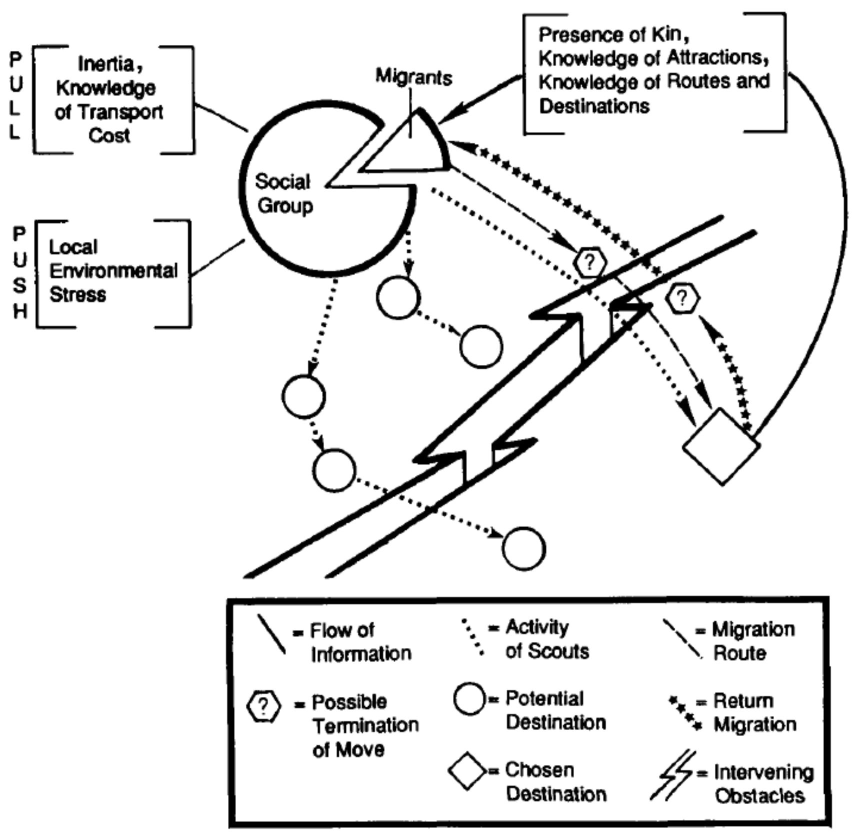


Figure 2.1: The complexities of the migration process as envisioned by Anthony (1990)

2.2 *Strontium isotope analysis and the study of migration*

In a move away from using indirect proxies as evidence for human movement, the main tool currently used to identify migration in the archaeological record is strontium isotope geochemistry. Pioneered by Ericson (1985) in archaeology, this technique uses the body's sequestration of strontium isotopes in skeletal tissues to establish whether or not an individual is local to a site. The technique itself is covered in more detail in section 8, but in essence it provides a more direct means of understanding migration. Instead of looking at a proxy for human movement it looks at the people themselves.

Strontium isotope analysis has been used to study migration in diverse areas and time periods archaeologically. Dental enamel is highly resistant to diagenetic change, and strontium isotope ratios within enamel can therefore give information not just about the archaeological, but also the paleontological past. Strontium isotope analysis has, for instance, been used extensively to look at hominin behavior and ecology. Sillen et al. (1998) used the technique to show the migration of hominin species, and the similarities between areas migrated from and to, to give information on habitat preferences. Movement within childhood of Neanderthals has been explored by Richards et al. (2008), to estimate the geographical ranges of Neanderthals.

Strontium isotope analysis has also been applied to anatomically modern humans to address important archaeological questions. Its application to Neolithic samples in Europe has confirmed the importance of migration as a process in the advent and spread of agriculture (Bentley et al., 2003), and the differences between 'settled' and mobile individuals during this period. The spread of the Bell Beaker people in Germany, Austria and Eastern Europe has also been explored using this technique (Price et al., 2004), to show hitherto unknown levels of mobility within single sites. Progress has moved forward rapidly with increased understanding of spatial variation in biologically available strontium, allowing better interpretation of results in archaeological contexts (Evans et al., 2010).

Strontium isotope analysis has also been used in the Americas, for instance, to show that unusual architecture in Teotihuacan, Mexico may be linked to non-local residents (Price et al., 2000), and that spatial patterning in the residences of locals and migrants is also apparent in the Pueblos of Arizona (Ezzo et al., 1997). Isotopic mapping has also been undertaken in this region to allow more accurate interpretation of strontium isotope results (e.g. Hodell et al., 2004).

Migration on an individual level is also routinely studied using strontium isotope analysis, both in archaeological and forensic contexts. It was famously used forensically to show the African origins of 'Adam' (O'Reilly, W., 2007), a torso found in the Thames. It has also been used to establish the region of origin of archaeological individuals such as the Iceman Ötzi (Hoogewerff et al., 2001), South American mummies (Knudson et al., 2005) and trophy heads (Knudson et al., 2009).

Strontium isotope work has also highlighted links between migrant origins and material culture, giving some support to the use of artefacts as proxies for human migration. Bentley et al. (2012), for instance, have shown links between adzes in mortuary ritual and access to loess soils for cultivation in Linearbandkeramik (LBK) sites of Europe. Conversely, ceramic vessels previously thought to relate to local origins have been shown to be present in graves of both local and non-local individuals at Grasshopper Pueblo (Ezzo et al., 1997).

Though there are problems in definitively identifying migration in the archaeological record, the assumption that prehistoric peoples were largely immobile has been rejected by most archaeologists (see Burmeister, 2000 for a review). It is now recognised that prehistoric peoples moved across the archaeological landscape for a number of reasons, as individuals, in small groups, or as large-scale diaspora, and this should be taken into account when considering prehistoric social organization.

2.3 Migration studies in Southeast Asian archaeology

Migration has long been thought of as an important process in Southeast Asian prehistory. Early archaeological research in Southeast Asia was conducted from the perspective that indigenous development of complex societies was highly unlikely (e.g. Coedes, 1969; Majumdar, 1944), and the area was something of a cultural backwater (Bentley, G., 1986; Bayard, 1980). From this point of view migration and culture contact were necessary for states to have developed, and debate raged over whether states in Southeast Asia were the product of conquest by China or India, settler colonies or political acquisitions (Coedes, 1968).

The lack of consideration for the possibility that state society may have been an indigenous development is at least partially due to the type of evidence used to reconstruct Southeast Asian prehistory. Early work was primarily based on written sources, which emphasise the role of foreign powers, downplaying the more everyday details of life in the past represented by material remains (e.g. Hooker, 1978; Hutterer, 1982a; Stark & Allen, 1998). This is particularly relevant in Southeast Asia, where historical records do not adequately document the transition to state society, leading some to dub this time the “twilight zone of history” (Hutterer, 1982a: 562). A dramatic increase in archaeological excavation in Southeast Asia has done much to redress this balance, and it is now recognised that social complexity is likely to have arisen *in situ* across Southeast Asia (Bentley et al., 2005; Cox et al., 2011; Higham & Kijngam, 2009; Winzler, 1981).

While migration is unlikely to have been as important as early researchers suggested, it was undoubtedlyat least partially responsible for other important societal changes. Migration from China, for instance, has been invoked as an explanation for the advent of agriculture in Southeast Asia (Glover & Higham, 1996; Higham, 1996a). Since the transition to an agricultural economy results in dramatic changes to society, this is very relevant to this study of social complexity in Southeast Asia. This topic is therefore covered in greater depth in section 4.

Migration is also considered by some to be an important process in the advent of metal-working in Southeast Asia (Higham, 1996b; 2002). Though this is rejected by some (Solheim, 1968; White, 2006), it nonetheless remains a possibility. Bronze smelting and casting first appears in the western provinces of China at around 2000BC (Higham, 2002), though parallels in technological advancement found in the near East suggest that knowledge of Bronze technology may have its origins further afield (An Zhimin, 1998). The spread of bronze casting techniques and artifact types can be traced along Neolithic trade routes (Higham, 2002), and it seems likely that at least some migration occurred alongside the transfer of technology. Similarly the knowledge of iron-working may have developed indigenously, but may also have been introduced from China (Higham, 2002), perhaps linking to further migration from this region.

Use of metal prestige goods also seems to have originated in China and spread into Southeast Asia. The most prominent example of this is that of the Dong Son drum. These large bronze vessels are found in royal graves of the Dian dynasty in China, but are also present throughout Vietnam and along the trade routes of Thailand (Higham, 2007).

It is clear then that people, non-local technology, ideas and material culture have moved throughout Southeast Asia in the past. The study of migrants and interpretation of their impact on society is therefore an important research topic.

2.4 Isotopic studies into migration in Southeast Asia

In order to establish the extent of migration in Southeast Asia a number of sites have been studied using strontium isotope analysis, though not all of these have been published (figure 2.2).

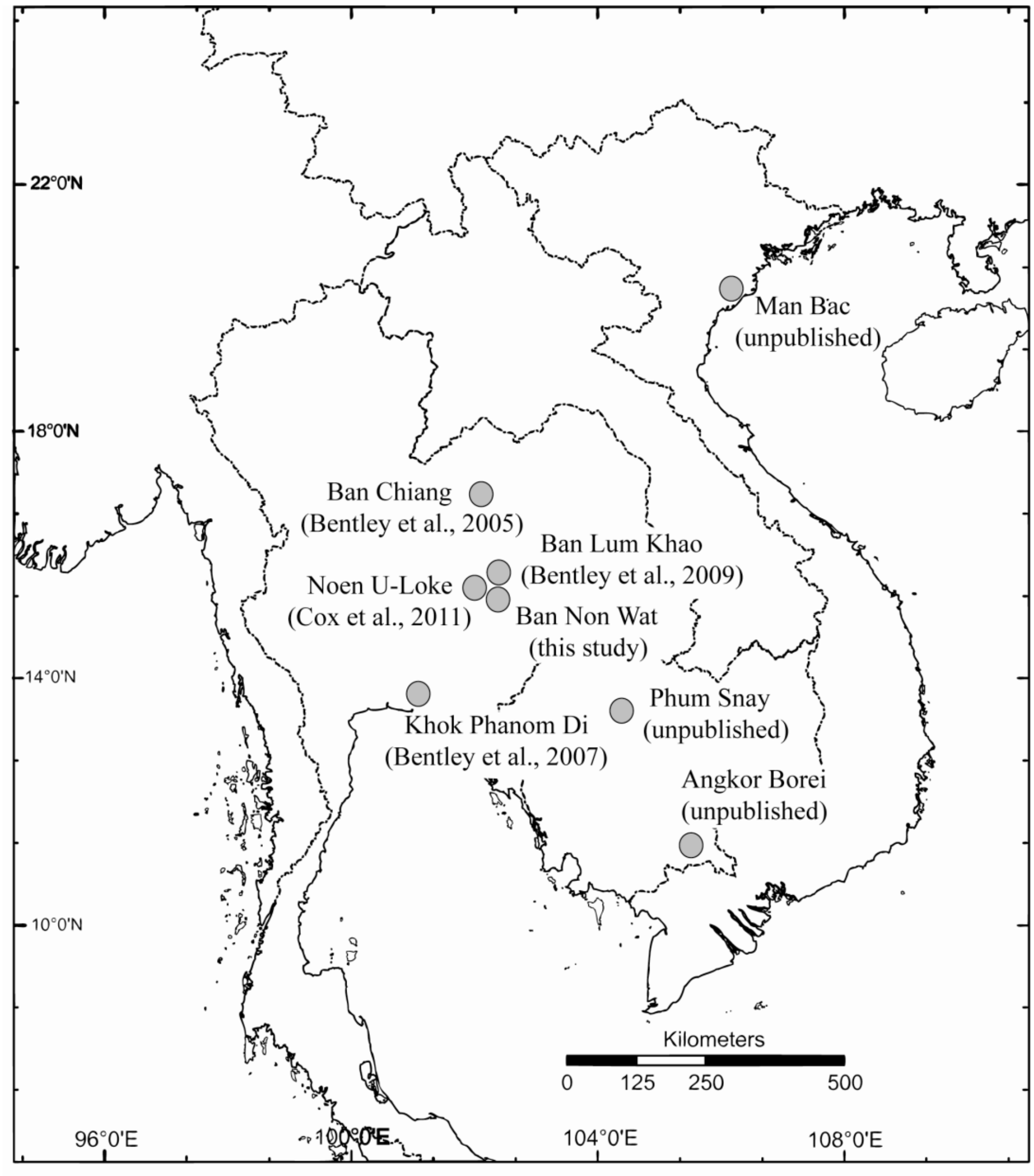


Figure 2.2: Map of the Southeast Asian peninsula showing the archaeological sites which have had strontium isotope analysis conducted at them.

At Khok Phanom Di, Bentley et al. (2007) used strontium isotope analysis to show that the majority of migrants to the site were found in the early phases of occupation, and most of these were female (figure 2.3). In later phases of the site's occupation local residence was the norm. A similar pattern was found at the northern Thai site of Ban Chiang (Bentley et al., 2005), leading the authors to suggest matrilocal residence patterns were a widespread pattern in later phases of Thai sites.

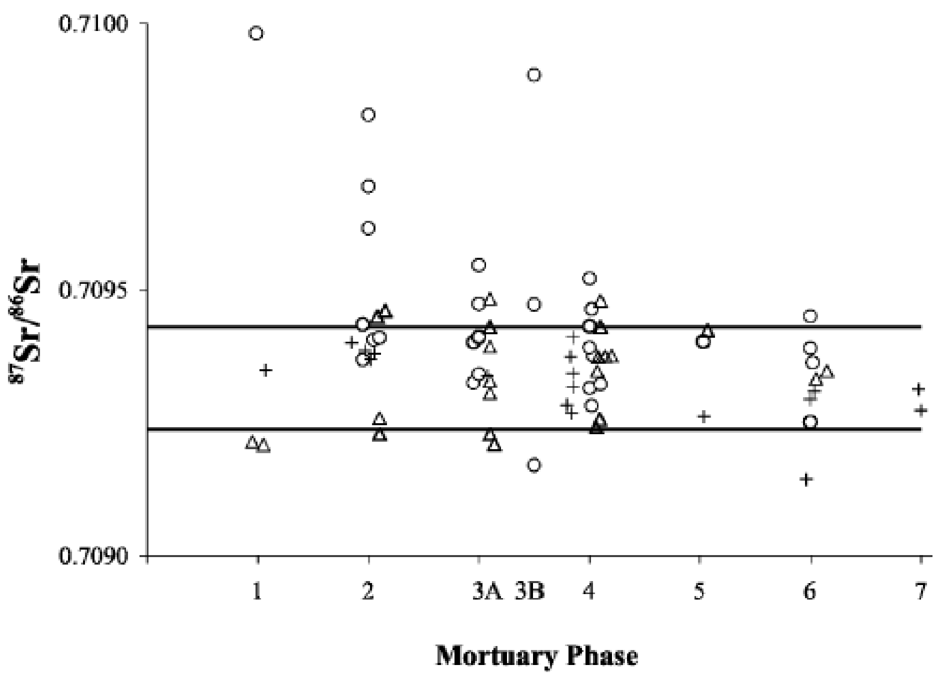


Figure 2.3: Strontium isotopic results from Khok Phanom Di (Bentley et al., 2007). Circles represent females, triangles males, crosses are sub-adults. Earlier phases of the site show more migrants, the majority of which are female

Previous isotopic studies in the UMRV, however, indicated that migrants were not prevalent in any period of the region's prehistory (Bentley et al., 2009b; Cox et al., 2011). These studies looked at the sites of Ban Lum Khao (Bentley et al., 2009b) and Noen U-Loke (Cox et al., 2011). Results of the study undertaken at Ban Lum Khao revealed only two individuals who were definitively identifiable as migrants, whilst the study at Noen U-

Loke found none at all. The sample sizes in these studies were, however, relatively small (*n*=27 at Ban Lum Khao, *n* = 34 at Noen U-Loke), and it is unlikely they fully describe the variation which is *actually* present within the sites. It was also recognized during these studies that the Upper Mun River Valley is remarkably homogeneous in terms of biologically available strontium, and so strontium isotope studies could not hope to identify short-distance migration.

Bentley et al.'s (2009b) study at Ban Lum Khao did, however, draw attention to correlations between isotopic results and the pottery type found in burials of women (figure 2.4), in that type 1 pottery seems to occur with women of higher $^{87}Sr/^{86}Sr$, types 5 and 6 with women of lower $^{87}Sr/^{86}Sr$. The authors interpret the differences in material culture as reflective of different natal settlements of the women. It is worth noting that the range of the y-axis in figure 2.4 is only 0.0004, almost within analytical error. If this is a significant correlation at all it is apparent that the natal settlements of these women are likely to be within the UMRV.

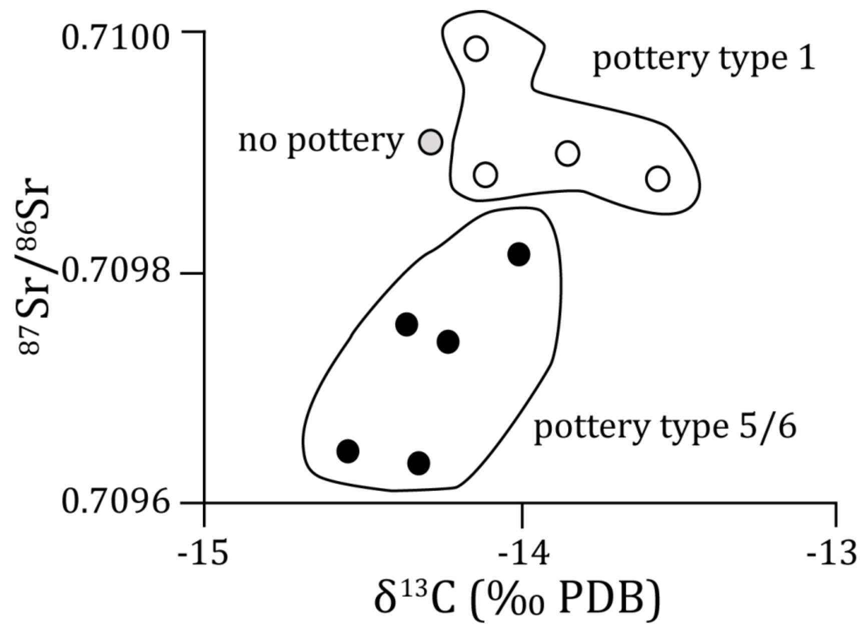


Figure 2.4: Isotopic results from Ban Lum Khao plotted with reference to pottery type found in the burial. After Bentley et al. (2009b).

Beyond Thailand, isotopic studies have not been quite so prolific. There is currently isotopic work underway in Cambodia by Nancy Beavan, which intends to use strontium isotope analysis to elucidate marriage patterns (Domett et al., 2011). There is also isotopic work which has been conducted at Man Bac in Vietnam, and Angkor Borei in Cambodia, the results of which are currently unpublished.

2.5 Non metric traits as a proxy for migration

While strontium isotope analysis is the mostly commonly used method for establishing non-local origins there are other lines of evidence which also link to population affinity. In this study dental non-metric traits are recorded, and cranial morphology analysed with the aim of establishing kinship and identifying individuals from different populations.

Variation in dental morphology was recognized as far back as the 1840s, when Carabelli wrote his seminal piece on the mesiolingual molar cusp (Hofman-Axthelm, 1981). Recognition that certain traits are more common in certain populations followed this, for instance the Uto-Aztecan premolar (Morris et al., 1978) is only known from native American populations, and shoveling of the incisors is more common in Asian and native American populations, less common in European (Carbonell, 1963). This led to the development of the idea of 'dental complexes', five to seven crown traits which are characteristic of a population (Scott & Turner, 2000). The idea of a Mongoloid complex, for instance, was developed by Hanihara (1968), while the Caucasoid complex was described by Mayhall and colleagues (1982).

Recent research using dental non-metric traits to assess population affinity often looks at the differences between more closely related populations than the broad-scale groups which were originally the focus for non-metric work. Modern studies involve the recording of non-metric trait frequencies, and calculation of population affinities using mean measure of divergence and Mahalanobis D^2 statistics (Irish, 2006). The mean measure of divergence statistic is a measure of dissimilarity, first employed by Berry & Berry (1967) to establish cranial affinity. In basic terms it establishes the difference in frequency of each trait between two populations, then divides this by the number of traits analysed to give a measure of difference between the populations (Harris & Sjøvold, 2004).The D^2 statistic was developed, to incorporate a correction for small sample sizes, and correlation calculations for inter-linked traits (Irish, 2010).

These techniques have been used with success to address archaeological questions of population affinity. Irish (2006) has used them to show population continuity between dynastic Egypt and Roman-period Egypt, but differences between these people and Greek Egyptians. Maximum mean divergence techniques have also been used to show population replacement leading up to state formation between earlier and later phases of Titicaca Basin sites, Peru (Blom et al., 1998).

2.6 Non-metric trait studies in Southeast Asia

In Southeast Asia non-metric trait recording has been used in multiple studies, often in combination with craniometric techniques, to establish population histories. One of the most in-depth studies of dental non-metric traits to have been undertaken in Southeast Asia was conducted by Matsumura & Hudson (2005). This study analysed the differences in non-metric trait occurrence between prehistoric sites in Thailand in order to establish relatedness between the populations. Results of the study indicate that while Hoabinhian sites have more in common with sundadont populations (i.e. Southeast Asia and the Pacific), sites from the Neolithic onwards show more similarity to East Asian and Northern Asian populations. This links well with the hypothesis that there was movement of agricultural populations from China during the Neolithic.

Studies involving non-metric traits have also been conducted by Hanihara (1992), Pietrusewsky (1994), Pietrusewsky & Douglas (2002), and Turner (1992). These have looked at the relationships between prehistoric and modern Southeast Asian populations to see if there is evidence for population replacement or change in the past, and show a continuity of population in Southeast Asia. The success of these studies shows there are differences in non-metric trait frequencies between the prehistoric populations of Southeast Asia, and these traits will be recorded as part of this study into population affinities.

2.7 Craniofacial morphology and its links to population affinity

Population affinity can also be studied using craniometric techniques. Craniometric studies use the basic principal that there are certain aspects of cranial morphology which are genetically dictated and thus differ between populations. Initial studies of populations using craniometric techniques were conducted with a Eurocentric slant, and this resulted in interpretations of cranial shape differences being used to perpetuate myths about the supremacy of European man (e.g. Hooton, 1931). Modern craniometric studies have, fortunately, moved away from this application and towards using craniofacial diversity to establish population histories. In order for this to occur many studies have been conducted to evaluate the how heritable cranial shape is, and therefore how representative of population affinity it may be.

Establishing which features of cranial shape are most related to population is complex as the skull is an integrated structure. Most regions are linked to others, and the shape of them is limited by the forces acting on, or functional constraints on the structure (c.f. Cheverud, 1988; Lieberman et al., 2004). Post-natal development and response to stress will change the shape of the cranium, no matter what the genetic background of the individual.

The cranial base is considered by most to be the oldest structure in the human skull, and therefore more strongly under genetic control (Martinez-Abadias et al., 2009). Conversely the shape of the face, which develops post-natally and responds to environmental and masticatory stresses, is likely to be most sensitive to non-genetic factors (Strand Viðarsdóttir et al., 2002). This response of certain cranial regions results to the environment results in a fundamental difference between craniometric and geneticdata. Craniometric differences between populations are perceived to be quite substantial (e.g. Hennessy & Stringer, 2002), contrasting with genetic information obtained using DNA analysis, which shows the majority of genetic variation occurs at a local level (Relethford, 2002).

There are a number of studies highlighting that cranial shape is the result of both genetic pre-determination and response to stress. As well as Strand Viðarsdóttir et al.'s (2002) study which showed the plasticity of facial growth in humans, Roseman & Weaver (2004) have also used craniometric data in combination with geographic and climatic data to show that measurements on the face (particularly the nasal and zygomatic heights) are closely related to climatic variation. Harvati and Weaver (2006) found that the shape of the temporal bone and basicranium could be most successfully linked to neutral genetic data, whilst facial shape was only weakly linked to genetic groups and more strongly affected by climatic variables. Hubbe et al. (2009) have added to this work through their analysis of over 7000 modern human crania. Their results highlight the fact that morphological variation in the vault can be explainedby geographic factors, while the face is more linked to climate. They also highlight links between certain climatic variables and craniometric variation e.g. level of precipitation correlates strongly with changes to nasal breadth, cranial breadth appears to be linked to humidity.

Studies of samples of known pedigree, however, have shown strong degrees of heritability in both cranial vault and facial measurements. A study of the Hallstadt collection, which represents a single closely related population, by Martinez-Abadias et al. (2009) used geometric morphometric techniques to examine which areas of the cranium are most heritable. The linear distances found to be most related to genetics were established using maximum likelihood methods (c.f. Koningsberg, 2000). They include the distance between the orbits, length of the nasal cavity, breadth of the skull, and length of the foramen magnum.Though this study focused on a single population of known pedigree, its results are relevant to craniometrics worldwide. They highlight that there is no significant difference in the heritability of dimensions between facial, basicranial and vault areas of the cranium, instead all of these regions may be useful in establishing population affinities.

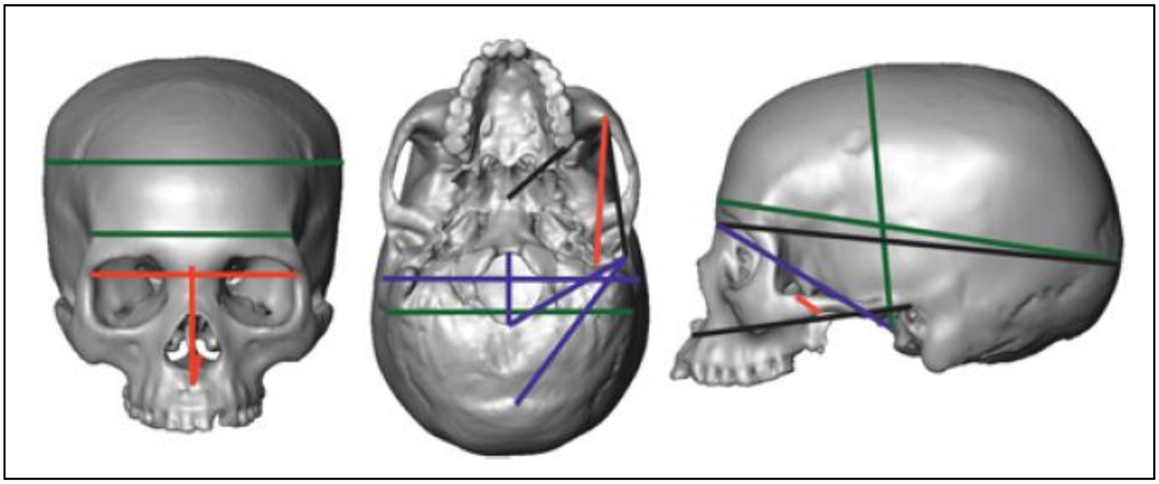


Figure 2.5: Showing the anterior, inferior and lateral aspects of the skull with cranial measurements of highest heritability indicated with lines (red – facial features, blue – basicranial features, green – neurocranial features, black – interregional features). Taken from Martinez – Abadias et al (2009).

Initial research into craniofacial morphology also suggested that regions which respond to the mechanical stress of mastication are unsuitable for use in population affinity studies

(Herring, 1993; Lieberman, 1995). This has been addressed by a geometric morphometric study by von Cramon-Taubadel (2009), which showed that though areas associated with masticatory muscles are indeed more variable in form, their measurements are still moderately to strongly heritable.

It is important to recognise the contribution of geometric morphometric analysis to the field of craniometrics. Looking at single measurements across the cranium cannot fully answer the question of how much cranial shape is genetically inherited and how much is associated with plasticity in response to the environment, as it does not assess individual regions as separate entities (instead they are linked through measurement). Traditional craniometric techniques also cannot differentiate between the relative contribution of shape and size (Hubbe et al., 2009). Many of the studies cited here use geometric morphometric techniques to resolve this, which allow the consideration of whole shape and portioning of shape and size data (e.g. Strand Viðarsdóttir et al., 2002; Harvati & Weaver, 2006; Smith, 2009; Martinez – Abadias et al., 2009).These techniques are also used in this study, and are covered in detail in section 11.

2.8 Studies of population affinity using craniometric techniques

Studies into the impact of genetics on cranial shape have established the validity of using craniometric data to establish population affinities in modern and archaeological populations. This area of research is therefore an expanding one in the field of archaeology. It was pioneered by Howells (1973; 1989; 1995), who used craniometric data from six regionally defined groups to establish world-wide cranial shape variation and the measurements which were most useful in establishing ‘ethnicity’. Howells’ sample has since been re-analysed in multiple studies (e.g. Relethford, 1994; 2002; Roseman & Weaver, 2004). Relethford’s (2002) study compared craniometric data to genetic results to show that craniometric data can be correlated to DNA polymorphism data, but does not match well with neutral genetic data. These results imply an ‘isolation by distance’ model of human evolution (Hubbe et al., 2009). Roseman & Weaver’s study (2004) used Howells’ collection to establish the selection pressures which have resulted in craniometric differences between populations.

Use of craniometric data to assess population affinity has been successful in many regions, looking at diverse periods of human history. Neves et al. (2005), for instance have used craniometric data to propose a dual-population colonisation of South America in the Pleistocene. Models of European Neolithic demic diffusion have also been tested using craniometric methods (von Cramen Taubadel & Pinhasi, 2011), to show physical dispersal of Near Eastern farmers into Europe and the splitting of this group into two discrete biological lineages.

On a more individual level, craniometric techniques have been used in both archaeological and forensic contexts to establish physical affinities of unknown individuals. Leach et al. (2010), for instance, have used craniometrics in combination with isotopic studies to highlight non-local individuals in Roman cemeteries and estimate their ethnic backgrounds. Craniometric assessment of population affinity has also been applied to the ‘Fort King George skull’, found in Georgia to show a New World affinity, rather than it representing a colonial individual (Stojanowski & Duncan, 2009). Use of craniometrics to establish racial affinities in forensic studies is commonplace (Ousley et al., 2009), often providing valuable clues to an individual's identity and aiding police investigations.

2.9 Craniometric studies in Southeast Asia

In Southeast Asia use of craniometric techniques as an aid to understanding the past is well-established.Research into population history in this region has primarily been undertaken by Pietrusewsky (1994; 1999; 2006) and Hanihara (1993; Hanihara & Ishida, 2008; Hanihara et al., 2008). These studies have given significant new information, with many now arguing for a continuity of population within Southeast Asia based on cranial similarities (Hanihara, 1993; Pietrusewsky, 2006). Links have also been established between the populations of Northeastern Asia and Japan (Hanihara et al., 2008), and the modern Southeast Asian populations and Neolithic Jomon populations of Japan (Hanihara, 1992).

Analysis focusing on the archaeological sites of the region has shown significant differences between coastal and inland sites in terms of cranial shape (Pietrusewsky, 1997; 2006), reflecting a prevalence of migrant peoples along the coast, or the persistence of hunter-gatherer communities in these areas. There has also been shown to be closer links between Jomon period Japanese individuals and Neolithic Thai samples than was previously thought (Pietrusewsky, 2006). Matsumura et al.'s (2008) work at Man Bac, Vietnam, has also been important in establishing Neolithic links with Chinese agriculturalists. Here the individuals interred have craniometric similarities with China, but little affinity with local Mesolithic Vietnamese populations.

These studies show that there are craniometric differences between the prehistoric populations of the Southeast Asian peninsula. This justifies the use of craniometric techniques, specifically geometric morphometric analysis, in this study, to further elucidate migration processes.

3. The Study of Social Structure

"One would seem ready to conclude that the chiefdom and all evolutionary typologies have outlived their usefulness and should be jettisoned"

-Earle, 1987 (pp. 280)

This study does not only look at migration and population affinity, it also studies kinship structures and social organisation in prehistory. Social organisation is often very complex, even in modern observable societies it is difficult to model. In past societies where only material culture remains, it is even more difficult.

3.1 Service's model of social evolution

In the past evolutionary models of social development have been employed to describe social order (Lubbock, 1869; Trigger, 1989). Developed following Darwinian principals these models viewed social systems on an evolutionary continuum, with modern 'savages' employing lower forms of organization, and 'civilization' representing the pinnacle of human achievement. Later models also viewed social organization as an evolutionary process. The most well-known of these models is Service's (1962), which describes the evolution of society from egalitarian bands through chiefdoms to state society (figure 3.1).

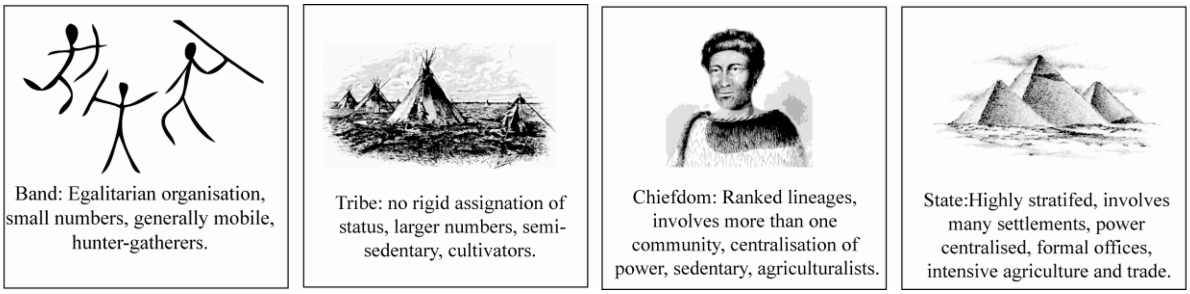


Figure 3.1: Service's (1962) typology of societies.

Service's model is a unilinear sequence of development, implying progress from one level of organization to the next was a prerequisite due to the selective pressures of more advanced societies (Trigger, 1981). Under Service's thinking, egalitarianism is the default social organization in humans, but tendencies towards inequality are common (Service, 1975). Movement towards a more institutionalized hierarchy therefore implies progress away from a base position. Formalised hierarchy is present from Service's 'chiefdoms' through to fully fledged state society. Hierarchical organization is also present within bands and tribes, but this is based more on individual leadership, not hereditary rank.

3.2 The characteristics of hierarchy

The concept of hierarchy and social organization is one of constant research (see Stark, 2006 for a review) but in essence hierarchical organization implies levels of society, led by an elite class who exert authority over the lower classes. Power is centralized (e.g. Morrisson & Lycett, 1996), and the rank of the elite is usually hereditary (Peebles and Kus 1977). Control is exerted through taxation, or differential access to resources, goods or other aspects of the economy (Earle, 1987; 1991). Hierarchical societies have the ability to marshal large labour forces into public works, and thus are often characterized by monument building (Carneiro, 1981). Emergence of a hierarchy is usually linked to the ability to produce a surplus, in order that taxation may be imposed, and access to this restricted (Price, 1985). Warfare is generally inherent in a hierarchical system, as it consolidates the leadership of the elite, and enforces control of lands (Johnson & Earle, 1987).

3.3 Application of the hierarchical model in archaeology

The idea of hierarchy being the more 'advanced' form of social organization has been much abused in the past to justify colonial expansion into areas of 'less-developed' peoples (Lubbock, 1869). Modern thinking recognizes that inequality is always present in society, as is the potential for formalized systems of ranking (Ames, 2007), however the presence of a hierarchy is not necessarily required. It is no longer assumed that hierarchical society is inherently more advanced, or a necessary precursor to social change, but hierarchy is still viewed as common archaeologically.

Part of the reason for this is the growing idea that formation of a dominance hierarchy is innate to humans (Boehm et al., 1993; Boehm, 2000; Henrich and Gil-White, 2001). This certainly appears to be the case in our closest relatives; chimpanzees, bonobos and gorillas. It is also apparent that in the past 10,000 years human society has become more complex and this has been linked archaeologically to the existence of surplus resources, of which early agriculture was one source (Ames, 2007; Earle, 2000, Hayden, 1995).

Among the necessary (but not always sufficient) archaeological evidence for hierarchy are an increase in craft specialization, surplus production, emergence of ‘prestige’ goods, and the construction of labour intensive monuments (e.g. Carneiro, 1981). Areas within a site which appear to have restricted access (Earle, 2000), or differences in residence size (e.g. Cordy, 1981) may also be evidence for hierarchy.Differences in mortuary wealth are often interpreted as evidence for within-settlement hierarchy (e.g. Hayden, 1995), withthe presence of wealthy infant burials being particularly relevant as it implies inherited rank as opposed to achievement-based status (Peebles & Kus, 1977).

Notable differences in health or diet seen during osteological analysis may also imply resource restriction within certain levels of society (Price, 1985). These phenomena, when found archaeologically, imply a level of social differentiation, often described using the hierarchical model, with the assumption being that any evidence for inequality is also evidence for a hierarchy (O’Reilly, 2003).

In fairness, there are many instances in which this is likely to be the case. The presence of ‘state’ societies implies at least some level of hierarchical organization. Inscriptions from the Cambodian state of Angkor, for instance, indicate that the King was divine, that their rank was hereditary (at least to some extent), officials were ranked, and taxes used to control the lower classes (Higham, 2002). All of these are unarguable characteristics of hierarchy, and appear common to most states.

There is, however, evidence that many archaeologically recognized ‘chiefdoms’, did not necessarily employ strict hierarchical organization. Other theories of social organization must be employed in these cases to explain what is seen in the archaeological record.

3.4 Heterarchical organization

The concept of heterarchy has been introduced to archaeology to address the growing recognition that human interactions can rarely be reduced to a vertical hierarchy (Brumfiel 1995; Flanagan 1989; Stein 1998), and allow the complexity of status assignation to be recognised (Crumley, 1995). In a heterarchical society it is recognised that there are multiple factors which affect an individual’s status, including personal wealth, family ties, social function and personal merit (White 1995; O’Reilly, 2000). An individual’s status has the potential to change depending on the context in which they are viewed, and there are numerous possible ways of ranking. Suggesting heterarchical organization is in place does not imply any specific type of social organization, but more that a different way of thinking about society is required (Stein, 1998). This means there are no strict rules for recognizing heterarchy and the presence of it archaeologically is hard to define (O’Reilly, 2003).

It should be noted that hierarchy and heterarchy are by no means mutually exclusive. Hierarchies may exist within a heterarchical organisation scheme, or vice versa (e.g. Scarborough et al., 2003) and it is possible that some combination of the two systems was in place in throughout prehistory. The debate over the form social organization took in prehistory cannot be resolved without consideration of as much information as possible. It is hoped that this study will add to the body of data available regarding the Upper Mun River Valley of Thailand, and clarify the situation there.

4. Subsistence Strategy – Agriculture and mixed economies

"The first revolution that transformed human economy gave man control over his own food supply"

- *Childe, 1936 (p. 66)*

4.1 The agricultural revolution

A final area to be considered in this study is the timing of agricultural intensification in Southeast Asia. The timing of the agricultural transition is related both to climatic conditions and social organization; study of it therefore helps to address the key theme of this thesis, social development. In this section the nature of the agricultural transition world-wide is considered, as well as evidence for how this might relate to the situation in Southeast Asia.

The term 'agricultural revolution' was coined by Childe (1936) to describe what he saw as the swift and complete change to European society upon the introduction of agriculture. More recent research into the introduction of agriculture to Neolithic Europe has confirmed this idea (Richards et al., 2003; Rowley-Conwy, 2004; Schulting & Richards, 2002). Rowley-Conwy (2011) has persuasively dispelled the idea that there were low levels of agriculture present in the late Mesolithic, showing the transition to agriculture as even 'more abrupt than has previously been envisioned' (Rowley-Conwy, 2011: 431).

Agriculture was introduced to Europe between 7000 – 5000BC (Whittle, 1996; Pinhasi et al., 2012), through immigration from the near East. Initially a single wave of advance model for agricultural spread was advocated (Ammerman and Cavalli-Sforza, 1984), which considered admixture explicitly, and now it appears that several migrations occurred and that sex-specific genetic admixture between incoming farmers and local hunter-gatherers is a distinct possibility (Bentley et al., 2009; Pinhasi et al., 2012; Rowley-Conwy, 2011; Rasteiro et al., 2012).

The advent of agriculture in Europe is characterized by the introduction of a new material culture suite and sedentism (Price et al., 1995; Zvelebil & Lillie, 2000; Childe, 1936; Cauvin, 1994; Hodder, 1990), and has also been linked to the emergence of social differentiation (Bogaard et al., 2011; Bentley et al., 2012). It is also widely held that the introduction of agriculture resulted in a decline of matrilocal and matrilineal communities. Male control of livestock in agricultural systems favours patrilineal descent (Bentley et al., 2007; Holden & Mace, 2003; Bentley et al., 2002), and the introduction of agriculture into forager society seems to have precipitated its rapid uptake through competition for brides. This process, known as the availability model, was advocated by Zvelebil and collegues (Zvelebil & Rowley-Conwy, 1984; Zvelebil & Lillie, 2000; Zvelebil, 2006), is summarized in figure 4.1.

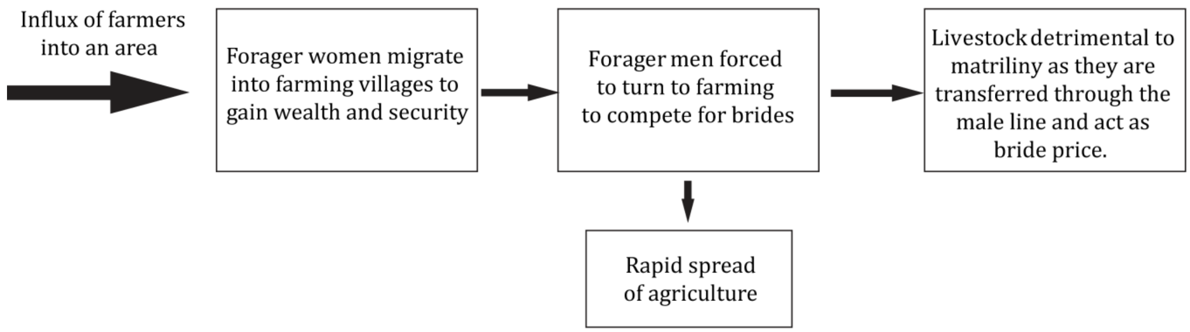


Figure 4.1: The process of the agricultural transition in Europe as proposed by Bentley et al. (2002), and its links to the decline of matrilineal systems.

4.2 Mixed economies?

The swift uptake of agriculture seen archaeologically in Europe is not necessarily common world-wide. Agriculture may form only part of the economy, with broad-spectrum hunting/gathering activities still used to supplement the diet. This has been observed ethnographically in the Dakota Native Americans who were observed to combine maize cultivation and hunting activities (Layton et al., 1991) at the point of colonial contact. Mixed economies have also been observed in Southern New Guinea (Lourandos, 1980), the Democratic Republic of the Congo (Biebuyck, 1973) and the Kubu of Sumatra (Sandbukt, 1981) to name but a few. In fact world-wide a total dependence on agriculture is very unusual (figure 4.2), and ‘middle-ground societies distinct from both hunter-gatherers and agriculturalists do exist (Smith, 2001).

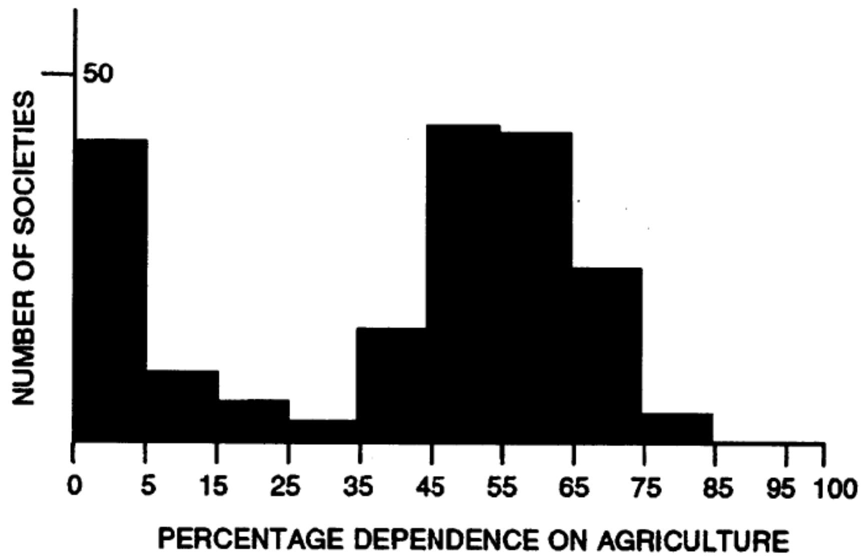


Figure 4.2: Showing the relative dependence on agriculture in 200 ethnographically observed societies (from Smith, 2001).

Symbiosis between hunter-gatherers and agricultural communities is also observable ethnographically, and results in supplementation of the diet by wild food sources, despite agriculturalists not engaging in hunting activities themselves. The most well-known example of this is symbiosis between the Mbuti and Bantu peoples of the Democratic Republic of the Congo (Turnbull, 1965). Here the Mbuti are hunters and exchange wild game, honey and forest materials for the manioc, bananas, corn and rice of the agriculturalist Bantu people.

Mixed economies are also proposed in archaeological contexts. Legge & Rowley-Conwy (1987), for instance interpret gazelle bones in Near Eastern sites as evidence of persistence of hunting behavior. In Scandinavia, Eriksson (2008) has used isotopic analysis to show the persistence of dietary diversity beyond the initial introduction of agriculture and throughout the Neolithic. Closer to the area of interest in this study Turner's (1979) work on the frequency dental of caries in cemetery samples has shown that Jomon period Japanese individuals have an incidence much more similar to those found in mixed economies than hunter-gatherer. Habu (1996) has used archaeozoological lines of evidence to support this, showing that the assumption of full sedentism in Jomon period Japan is flawed, and that mixed economies and seasonal movement were common.

4.3 The agricultural transition in Southeast Asia

It is generally accepted that rice agriculture was developed in the Yangtze Valley of China during a warming after the Younger Dryas Period, though exact evidence for when this occurred has not yet been uncovered (Higham, 1995; Cohen, 2002; Fuller, 2006). Conservative estimates place its origin at around 6500BC (Bellwood, 2005).Millet was first domesticated in the Huang Hi valley in the colder North of China (Barton et al., 2009). It is widely believed that early agriculturalists expanded into mainland Southeast Asia from these centres in roughly the 3rd millennium BC, taking with them their domesticated crops and culture (Higham, 1995).

Archaeological evidence from Southeast Asia suggests that the introduction of agriculture was characterized by the replacement of Holocene hunter/gatherer culture complexes with the pottery, stone adzes, spindle whorls, shell ornaments and faunal remains of domesticated bovids, suids and dogs common to early agricultural society (Bellwood, 2005; Higham, 2002). This transition has in the past been taken to have a certain 'orderly precision' to it, with agriculture inexorably progressing from Southern China through mainland Southeast Asia and into Island Southeast Asia (Bellwood, 2005: 130).

Multiple lines of evidence, however, have now been brought to light which go against this idea of a 'revolutionary' introduction of agriculture in Southeast Asia. In Thailand there is evidence for the persistence of matrilocal systems far beyond the advent of agriculture (Bentley et al., 2005), to the extent that matrilineal systems are still in place today in many parts of Thailand (Walker, 2006). Added to this is the idea that broad-spectrum hunting persisted alongside agriculture well into the Neolithic and possibly the Bronze Age (Bellwood, 2005). This is claimed at the site of Ban Chiang where archaeozoological evidence suggests a mixed economy involving the harvesting of natural resources (e.g. game, wild fruits, fish), as well as use of domestic animals and cultivation of rice and yams (Higham & Kijngam 1979; White 1995b; Pietrusewsky & Douglas, 2002) . This is supported by isotopic evidence from Ban Chiang, which shows a varied diet involving both wild and cultivated resource throughout the Neolithic (King, 2008).

The decline in health and increase in population typical of farming communities in the European Neolithic (e.g. Jackes et al., 1997; Larsen, 1995; Cohen & Armelagos, 1984), also does not appear to be present in Southeast Asia until the Iron Age (O'Reilly, 2000; Pietrusewsky & Douglas, 2002). Does this mean that agriculture was not relied upon until this point in time? The timing of agricultural intensification remains an important question in Thai archaeology and will be addressed in the course of this research.

5. Archaeological Context

"It is interesting to note that even in prehistoric times the autochthonous peoples of Indochina seem to have been lacking in creative genius and showed little aptitude for making progress without stimulus from outside"

- *Coedes 1969 (p.13)*

5.1 Introduction

Southeast Asia is one of the most exciting arenas of archaeological research. It played host to some of the world's most famous civilisations such as Angkor as well as the state societies of Funan, Chenla, and Dvaravati, but the prehistory of the region is still not fully understood. Archaeology in the region, by world standards, is a relatively recent development. This means that every study has the potential to dramatically change what is known about the past.

In order to place this study in context a rough chronology of the region is provided in figure 5.1. The focus of this study is on prehistoric occupation, from the Neolithic to the Iron Age, though the nature of prehistoric society obviously has a consequent effect on 'state' society in the region.

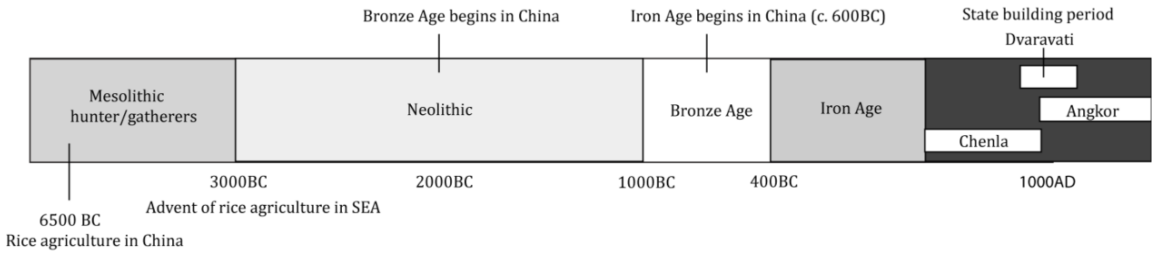


Figure 5.1: Timeline showing periods in the history of Southeast Asia. Dates are approximate (from Higham, 2002; O'Reilly, 2007) as different parts of the region experienced transitions at slightly different times, and some phases are entirely absent in some areas (see section 5.2)

As with all areas of archaeological research there are a number of contentious issues in Southeast Asian prehistory, some of which are relevant to and will be addressed within this study. Chief among these is the relevance of the three age system to Southeast Asia. There is growing awareness that Southeast Asia appears to have had differential involvement in the metal ages (see section 5.2), and thus the characterisation of periods based on metal technology is not appropriate. In this study the terms of the three age system are used to give consistency with previous research in the area, but their limitations are noted.

The awareness of social diversity in the region has also led to debate over whether hierarchical models of social organisation are relevant. The apparent autonomy of settlements, lack of an obvious social elite in some sites, and problems relating the presence of metalwork to status, mean that many are turning away from traditional models towards more flexible perceptions of the past. This debate is detailed in section 3 and its relevance to the UMRV in section 5.5. Finally, there is debate over the nature and timing of agricultural intensification in Southeast Asia, as detailed in section 4.3.

Only future archaeological research will resolve these issues, and this thesis adds evidence to two of them. By studying kinship with reference to status indicators such as diet and mortuary wealth it adds new evidence to the hierarchy/heterarchy debate. Dietary isotope work also gives further information regarding the timing of agricultural intensification in the Upper Mun River Valley.

5.2 Southeast Asian Prehistory

Although this study looks specifically at the evolution of society in the Upper Mun River valley it is useful to place this area in its geographic and historical context.It is accepted that Southeast Asia experienced a growth in social complexity during prehistory, but the nature of this growth is not yet fully understood. There are differences in material culture and mortuary wealth between individuals of contemporaneous phases of almost all prehistoric archaeological sites in Southeast Asia. These become particularly obvious after the advent of bronze technology, around 2000BC (Higham, 1996b; Higham & Kijngam, 2009; Higham & Thosarat, 1994; O'Reilly, 2008). Changes, however, do not appear to be uniform, and the character of inequality varies between sites and regions, meaning generalisations about social structure cannot be made (Eyre, 2010).

It was noted by Muhly (1988) that the character of the Bronze Age in Southeast Asia is very different to that of the rest of the world. In all other areas the advent of bronze technology correlates with the ‘rise of the state’, and “only in Southeast Asia, especially in Thailand and Vietnam, do the developments seem to be missing” (Muhly, 1988: 17).

This may be due to Southeast Asia’s non-uniform involvement in the Bronze Age. Evidence from Western Thailand suggests that this region did not experience a Bronze Age at all (Glover, 1991), transitioning instead from stone to iron technology. White & Hamilton (2009) also suggest that evidence for metal-working in some but not all contemporaneous sites in Southern Thailand is evidence for differential involvement in production circuits.

Dealing with the anomalous nature of the Bronze Age has led to two different approaches to archaeological interpretation in Southeast Asia. The first is to advocate short chronologies of development, and increase attempts to find evidence of an elite and hierarchy (e.g. Higham & Higham, 2009). The second is to investigate ways in which a Bronze Age could have occurred slowly, based on household production centres, without a hierarchy developing (White & Hamilton, 2009; White, 1995; O’Reilly, 2003). These alternative responses to the archaeological problem of Southeast Asia’s Bronze Age have led to a great deal of debate surrounding modes of social organisation. This is covered in detail, with reference to the UMRV in section 5.5.

The Iron Age seems to be more universally identifiable across Thailand. Iron is the first metal to be present in any quantity in Western Thai sites such as Ban Don Ta Phet (Glover, 1990; 1991). In other areas of Thailand, where there is evidence for a Bronze Age, the advent of iron technology coincides with bronze becoming more ornamental and the increasing use of iron for tools (Higham, 1996a). There is also evidence for large-scale mobilisation of labour to create moats in the Iron Age of northeast Thailand (detailed in section 5.5)

5.3 State Society in Southeast Asia

As detailed in section 2 early archaeological investigation of Southeast Asia focused on the rise of state society in the region. It was often assumed that state societies had their origins externally e.g. China and India, and were brought in by immigrants from these regions (e.g. Coedès, 1968; Majumdar, 1944).

The state society most relevant to this study is that of Angkor, based around the Tonle Sap of Cambodia, but at its height stretching across Vietnam, Thailand and parts of Laos. It is generally agreed that Angkor arose from the pre-state society of Chenla in Cambodia, in approximately 800AD (O'Reilly, 2007). Angkor is characterised by centralised political systems, monument building and an expansion of controlled territory. In the past, Angkor has been assumed to have brought state society to the less advanced areas of Southeast Asia such as Northeast Thailand (Bayard, 1980; Fisher, 1964). The Origins of Angkor project was begun in 2000 to investigate whether or not this was the case, and the research presented here is connected with this project.

5.4 The importance of the Upper Mun River Valley

The Upper Mun River Valley was chosen as the focus region for the Origins of Angkor project due to its importance to the Angkorian Empire when at its height. It was annexed by

Angkor in approximately 1100AD under the rule of Suryavarman I, and the regional centre of Phimai served as an Angkorian administrative centre for the next 300 years (Welch, 1998). Historical records from the Khmer period have identified the region's importance as centre of trading. It lay on major trade routes between Angkor itself and China, and was an important area in the exploitation of salt (Welch, 1998; Talbot & Chutima., 2001). It is likely that the Upper Mun River valley also occupied an important position in prehistory as an interface between the two cultural areas of Dvaravati and Angkor (Brown, 1996; O'Reilly, 2007).

The obvious presence of the Angkorian empire, and the likelihood of Dvaravati influence in the UMRV led early researchers of the area to question whether the rise of social complexity was intrinsic or brought about purely by intrusion of foreign populations (Coedes, 1969). In investigating this, attention turned to the nature of society prior to the advent of the Angkorian Empire, the prehistoric settlement of the area.

5.5 The moated sites of the UMRV

Moated sites were first identified in the UMRV through aerial photography in the 1940s (Williams-Hunt, 1948; 1949). Williams-Hunt first identified the locations of sites of archaeological interest, allowing subsequent research to expand knowledge of these sites through further aerial photography, field survey, and excavation (Villabhotama, 1984; Welch, 1983; 1984; Moore, 1988; Parry, 1992).

Recent investigation of these sites under the 'Origins of Angkor Project' has shed further light on the chronology and site development processes in the UMRV. Investigation of the moats themselves has primarily been undertaken by Boyd and McGrath (Boyd et al., 1999) and shows that the moats of almost all the UMRV's sites were built in the Iron Age. It appears that their purpose was primarily for water management, not defence.

Thorough archaeological investigation has identified a vast archaeological landscape within the UMRV, comprising of these moated, or multi-vallate, sites and smaller peripheral ones. Those which have received the most archaeological attention are marked on figure 5.2.

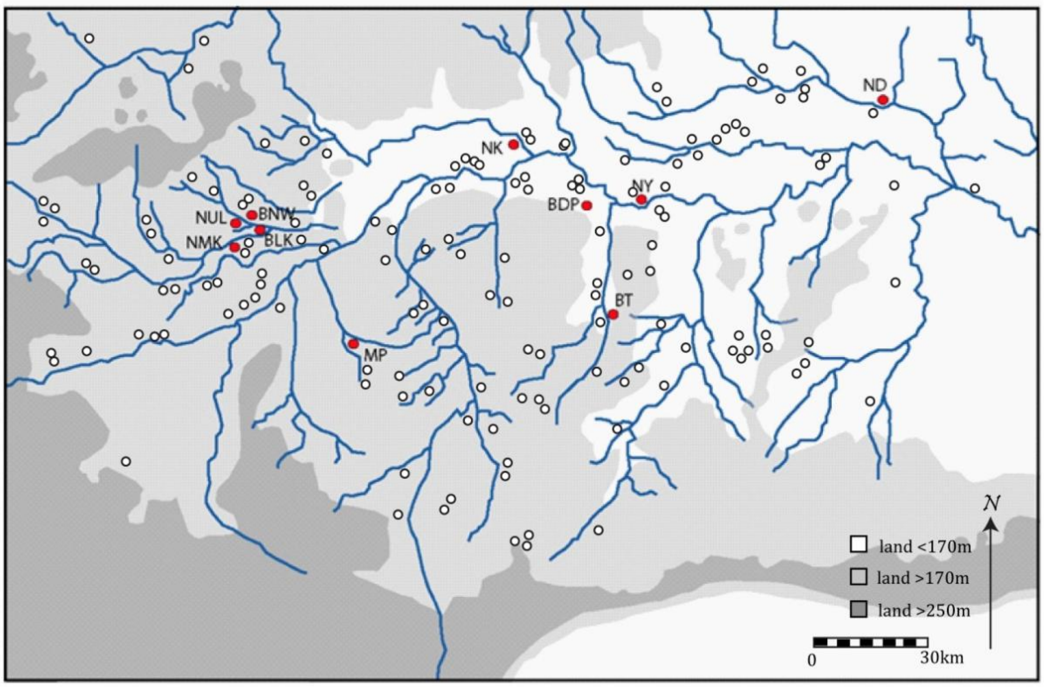


Figure 5.2: The known archaeological sites in the Upper Mun River Valley (after Higham & Kijngam, 2009). Sites which have been reported archaeologically are labelled. NBJ = Non Ban Jak NMK = Non Muang Kao, NUL = Noen U-Loke, BLK = Ban Lum Khao, BNW = Ban Non Wat, NK = Non Krabuang , BDP= Ban Dong Phlong , BT= Ban Takhong , NY= Non Yang, ND = Non Dua.

Extensive excavation has been undertaken at several of these sites, the best known being; Ban Lum Khao (Higham &Thosarat, 2005), Noen U-Loke (Higham et al., 2007) and Ban Non Wat (Higham & Kijngam, 2009), the subject of this study.

5.6 Growth in social complexity and debate over the nature of social stratification

The excavations of sites within the UMRV have echoed the findings at sites throughout Southeast Asia, showing a rise in social stratification and complexity from the Neolithic onwards. It seems likely that complex society arose intrinsically, without the need for foreign populations, such as the Khmer, bringing in ideas of social organisation (e.g. Bentley et al., 2007: 2009b), but to explore this possibility further one of the main aims of this study is to search for migrants in the UMRV.

While it is clear that there was social differentiation in the prehistoric communities of the UMRV it is unclear how status was assigned and inequality enforced. The two main schools of thought on social organisation, hierarchy and heterarchy are discussed in section 3, and both are considered possible explanations for the structure of society in the prehistoric UMRV.

White (1995a) interprets the lack of rigid rules for burial, continuum in terms of mortuary goods between individuals, the common occurrence of burials that stand out as distinctive in an individualistic sense, and apparent lack of centralisation of power as evidence of heterarchy in the region. Similarly, O'Reilly (2000; 2003) sees the apparent presence of household production centres (cf. White & Pigott, 1996) and lack of evidence for restricted access to resources, or inter-community violence in Ban Lum Khao and Noen U-Loke as evidence for heterarchical organisation. O'Reilly (2000) does concede that there is more evidence for 'entrenched' hierarchy after the advent of iron technology, linked to mobilisation of labour forces to construct moats, an increase in ritual activity and growth in population.

Conversely it is suggested that, unless all individuals have equal access to resources, some form of hierarchy must be in place (O'Reilly, 2003). This point of view is epitomised by Higham (2011; Higham & Kijngam, 2009; 2011). Though initial survey within the UMRV led Higham to initially assert that 'the attainment of status was flexible rather than fixed, and that the relative position of each autonomous settlement was given to fluctuation, and therefore instability' (Higham, 1989: 187), in recent years, following more extensive excavation this statement has been recanted (Higham & Kijngam, 2011).

The limited excavation of sites during early archaeological investigation of the valley did not allow accurate interpretation of the evidence. More extensive excavation of Ban Non Wat, it is argued, has revealed evidence for high levels of mortuary ritual and feasting and a correlation between the advent of Bronze technology and the presence of extremely rich burials (the 'super-burials' of Bronze Age 2). These factors suggest the maintenance of social elites (Higham, 2011), a level of inherited wealth (Higham & Kijngam, 2009) and the presence of social aggrandisers forming a social elite (Higham, 2011). These factors all link strongly to the concept of hierarchy within a chiefdom (Service, 1962; Hayden, 2001).

Currently a consensus seems unlikely between these two schools of thought, with differences in opinion arising at least partially because excavation has not been extensive enough to clarify the issue. It is true that, in the past, much of the research in the UMRV was conducted in pursuit of hierarchy (Eyre, 2010) and it is therefore unsurprising that this is what was reported. It is only now that archaeologists are seeking to break away from the Eurocentric models of social evolution, that other structures of social organisation are being considered. One of the aims of this research is to investigate this concept further, the results of which are presented in section 13.

5.7 Ban Non Wat

Ban Non Wat was excavated under the direction of Prof. Charles Higham and Dr. Rachanie Thosarat between 2002 and 2007. Excavation continues into the present under Dr. Nigel Chang and Dr. Amphan Kijngam. This study is restricted to individuals excavated in the first phase of excavation. This comprises the vast majority of the cemetery sample.

The excavation under Higham and Thosarat covered an area of $906m^2$, revealing 637 burials within 10 mortuary phases. These mortuary phases have been differentiated on the basis of burial orientation, mortuary goods and carbon dating (Higham & Kijngam, 2009). There are two supine Neolithic phases present at Ban Non Wat, and one flexed phase which seems to overlap temporally with some of the supine burials, but is interpreted by Higham & Kijngam (2009; 2011) as evidence for Mesolithic hunter/gatherers at the site. These are then overlain by five Bronze Age phases, and two Iron Age phases. Plans of the excavation square for each of the mortuary phases are given in appendix 1, with those individuals analysed in this study highlighted.

Grave goods indicate that inequality was present in some form at least at Ban Non Wat from the Bronze Age onwards. Mortuary wealth discrepancies reach their peak within the second Bronze Age mortuary phase. Higham describes the mortuary wealth in this phase as "a quantum leap over BA 1, and infinitely greater than at any other such site of similar age or cultural affiliation in Southeast Asia" (Higham & Kijngam, 2011: 369). Burials exemplifying the stratified nature of society during this phase are shown in figure 5.3. Rich burials are characterised by the inclusion of multiple ceramic vessels, bronze artefacts and exotic shell ornaments; whilst poor burials have little to no mortuary wealth associated with them.

Figure 5.3: B197, an example of a Bronze Age 2 super-burial (left) and B557 (right), an example of a 'poor' burial lacking in mortuary wealth. Photos courtesy of Dr. Nigel Chang and Prof. Charles Higham.

From the third Bronze Age phase at Ban Non Wat there is a continuation of mortuary wealth discrepancies between rich and poor, but differences become less marked, and no burials match the wealth seen in the second Bronze Age phase (Higham & Kijngam, 2011). Higham (2011) parallels this with findings in Bronze Age Europe, in particularly the highly decorated individuals of the early Bronze Age at Varna (Higham, T., et al., 2007). This has been interpreted as evidence for jostling for elite position upon first introduction of new bronze technology, with competition dying down once elite groups were decided upon. This led to less need for display of wealth through mortuary ritual in later Bronze Age phases (c.f. Childe, 1930).

Iron Age occupation is also evident at Ban Non Wat, beginning at approximately 400BC. There are four Iron Age mortuary phases evident at Ban Non Wat, characterised by the inclusion of iron tools, and the use of bronze for more ornamental purposes (Higham & Kijngam, 2009).

The chronology of mortuary phases at Ban Non Wat has been established by Higham and Higham (2009) through radiocarbon-dating and Bayesian modelling, and is presented in table 5.1.

Cultural period	**Date in calibrated radiocarbon years (BC)**
Flexed burials	1750-1050BC
Neolithic 1	1650-1250BC
Neolithic 2	1250-1050BC
Bronze Age 1	1050-1000BC

Bronze Age 2	1000-900BC
Bronze Age 3	900-800BC
Bronze Age 4	800-700BC
Bronze Age 5	700-420BC
Iron Age 1	420-100BC
Iron Age 2	200BC-200AD
Iron Age 3	200-400AD
Iron Age 4	300-500AD
Early Historic	500-

Table 5.1: Chronology of the burial phases at Ban Non Wat, based on radiocarbon determinations from BNW, NUL and BLK.

5.8 Sites used for comparative purposes in this study

Ban Non Wat is the focus of this study, and all original results reported in this volume are the result of analysis of Ban Non Wat's cemetery sample. In order to study regional patternsother previously studied sites have been looked at for comparative purposes. Ban Lum Khao and Noen U-Loke lie within a 15km radius of Ban Non Wat. They are also moated sites, and were excavated prior to Ban Non Wat by Prof. Charles Higham and Dr. Rachanie Thosarat in 1995-6 and 1997-8 respectively.

Neither Ban Lum Khao nor Noen U-Loke were as extensively excavated as Ban Non Wat has been, and samples analysed isotopically in previous studies are not nearly as large as the one reported here; only 27 individuals from Ban Lum Khao, and 34 individuals from

Noen U-Loke have been analysed isotopically (Bentley et al., 2009b; Cox et al., 2011). This means that samples may be biased e.g. if the richest parts of the cemeteries remain unexcavated. This has been taken into account in interpreting comparative data (section 14).

Occupation at Ban Lum Khao and Noen U-Loke overlaps temporally with some of the phases at Ban Non Wat (O'Reilly, 2000; Higham et al., 2007), but there are no Neolithic burial phases present at Ban Lum Khao and Noen U-Loke is a later site, with occupation primarily during the Iron Age. The contemporaneity of phases between the sites is illustrated on figure 5.4.

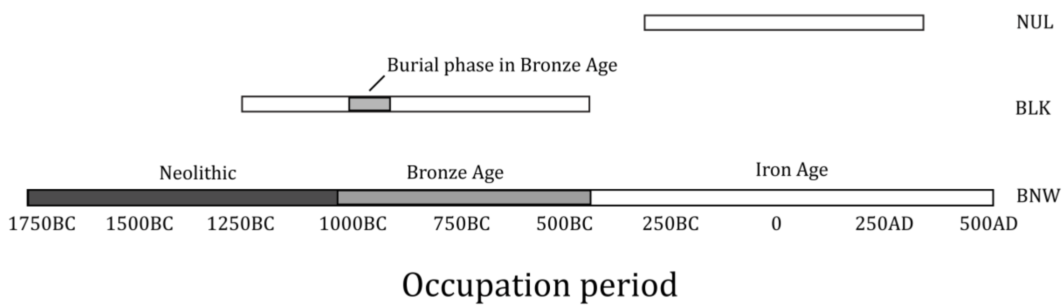


Figure 5.4: The occupation periods of the sites focused on in this study. BNW = Ban Non Wat, BLK = Ban Lum Khao, NUL = Noen U-Loke.

There appears to be a level of continuity of culture between the sites of the UMRV i.e. ceramic form and style, artefact type and many aspects of mortuary ritual are shared between the sites (Higham & Kijngam, 2012). There are, however, notable differences between them which are not yet fully understood. The culture at Noen U-Loke, for instance, seems to ascribe a much greater ritual importance to rice, with its incorporation into burial ritual in the later phases of the site being evidence for this (Higham et al., 2007).

There also appears to be a large discrepancy in mortuary wealth between Ban Non Wat and contemporary phases at Ban Lum Khao (Higham & Kijngam, 2012). The Bronze Age burials of Ban Non Wat include bronze artefacts, large numbers of ceramic vessels and exotic artefacts such as shell beads. Those at Ban Lum Khao do not involve bronze or exotics and have far fewer ceramic vessels. Higham & Kijngam (2012) note that even the poorest individuals in the second Bronze Age phase at Ban Non Wat are richer than any of their contemporaries at Ban Lum Khao. This leads them to suggest differential involvement in trade and access to resources between the sites of the UMRV, though it has been suggested that limited excavation at Ban Lum Khao may have biased the sample there (Higham & Kijngam, 2011).

5.9 Summary

The Upper Mun River Valley provides a useful arena through which to explore processes of social evolution during prehistory. Not only did the region play an important role in the historic period, it also appears to have been a significant region prior to incorporation in a state-level society. The richness of the archaeological record in the UMRV means that social evolution can be traced from initial settlement over 2000 years of occupation. Extensive archaeological investigation in the area also means that sites can be considered as part of the archaeological landscape through comparison with one another.

In this study social evolution is traced by focusing on the site of Ban Non Wat, but comparison of results will be made to those already obtained from Noen U-Loke and Ban Lum Khao in order to establish whether the processes seen are universal and evaluate the homogeneity or lack thereof across the archaeological landscape.

6. Materials

In this study osteological and isotopic analysis was out upon a sample from the site of Ban Non Wat. This site has been previously detailed in section 5. Overall 144 individuals from Ban Non Wat's cemetery were analysed, as well as 5 faunal samples which were taken to establish the local isotopic range.

6.1 Teeth sampled

Isotopic analysis was conducted using samples of dental enamel. The permanent second molar was sampled preferentially for this study. The crown of this tooth, and therefore the area sampled during this study, mineralises between 3-7 years (Hillson, 1996), and isotopic ratios obtained from this tooth will reflect the individual's childhood home geology and diet.

If no second molars were present in the individual, or the tooth did not have an antimere then a different tooth was sampled. If this was the case, then premolars were preferred for sampling – as isotopic ratios from the crowns of these teeth reflect conditions between 2 and 7 years of age (Hillson, 1996). First molars and incisors were considered the least preferable samples as their mineralisation begins *in utero* and therefore partially reflects the mother's diet. The tooth sampled from each individual analysed is given in table 1 of appendix 2.

6.2 Demography of the Ban Non Wat Sample

In this study the sample was weighted based on the total number of individuals in each mortuary phase (i.e. more individuals were sampled from larger mortuary phases), in order to ensure that the samples were representative of their phase. Roughly equal numbers of males and females were included, although preservation issues meant a completely even representation was not possible. Biological sex was established using standard osteological sexing methods (Buikstra & Ubelaker, 1994).

The age at death of the individual is in many ways irrelevant to this study, as isotopic ratios in dental enamel reflect an individual's childhood, and will be unchanged no matter what the individual's lifespan. Nonetheless age at death of individuals is given here as a matter of interest. Age categories used in this study are young, young-mid, mid, mid-old and old. Definite ages in years are not given, as most aging standards e.g. Lovejoy et al. (1985), the Suchey-Brooks methods (Suchey et al., 1986), Scott (1979), have not been well-tested on Asian populations. Indeed, those tests which have been conducted suggest that these standards should be applied with a great deal of caution as age ranges at the different osteological stages do not fully align with those populations the standards were designed for (e.g. Schmitt, 2004). In order to overcome this only broad age categories were used, and table 6.1 gives the stages which correspond to each of these.

Age category	Pubic symphysis stage (Suchey Brooks method)	Auricular surface stage (Lovejoy et al., 1985)	Sternal rib end stage (Işcan et al., 1984)	Dental wear (Scott, 1979) on each molar (composite score for all molars)
Young	1	1	0	1 (<12)
Young-mid	1-2	2-3	1	2-3 (12-36)
Mid	3-4	3-4	2-3	3-4 (36-48)
Mid-old	4-5	4-5	3-4	4-6 (48-72)
Old	5-6	6 +	4-5	6 + (>72)

Table 6.1: Explanation of the aging categories using in this study, and the stages in traditional aging standards that they correspond to.

Sub-adult teeth were not analysed in this study, partially because the second molar would not be fully erupted on all subadults, but also because the study aimed to use the same individuals for isotopic and osteological analysis. Craniometric analysis was not conducted on subadults, as the effects of allometry would obscure population-based cranial shape differences. In addition to these reasons subadult teeth are rarer in the site, and are being examined in a concurrent study by Dr. Sian Halcrow (University of Otago), and so sampling of these was neither possible nor necessary.

The demography of the sample taken from each mortuary phase is given in figures 6.1 to 6.10.

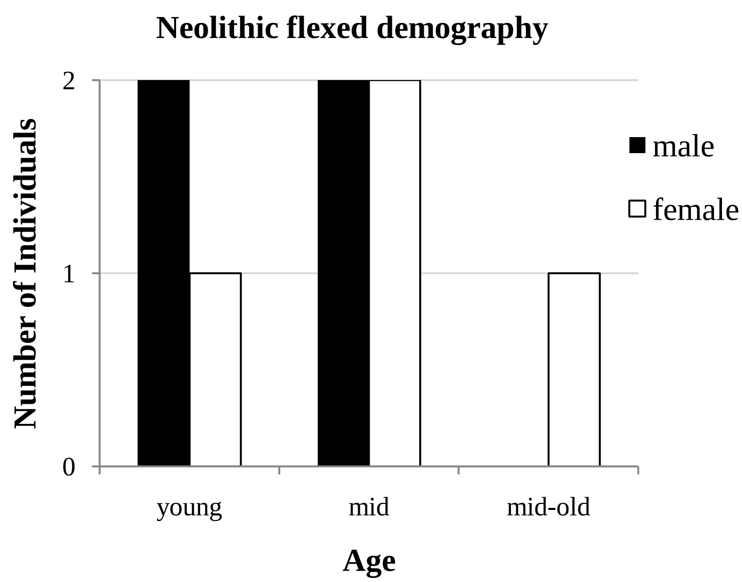


Figure 6.1: The demography of the sample taken from the Flexed Neolithic phase.

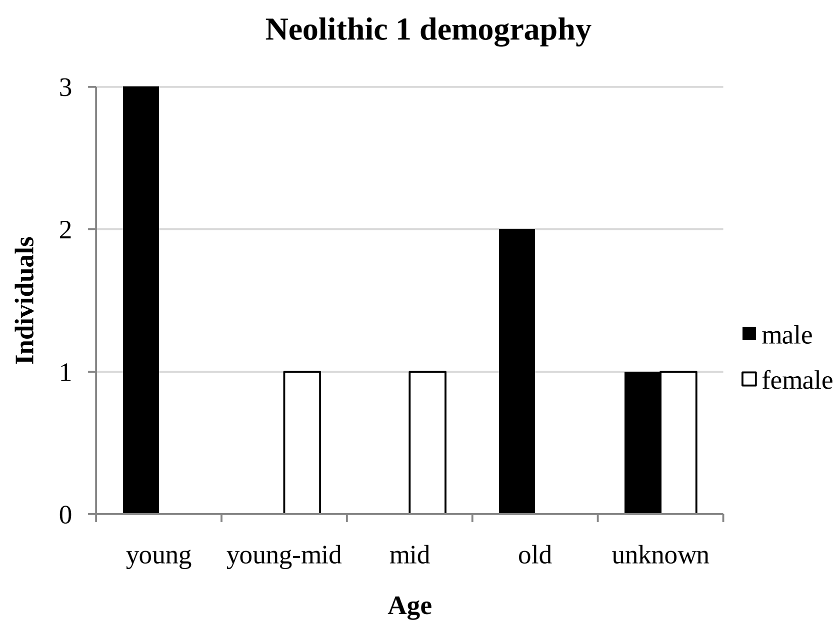


Figure 6.2: The demography of the sample taken from mortuary phase Neolithic 1

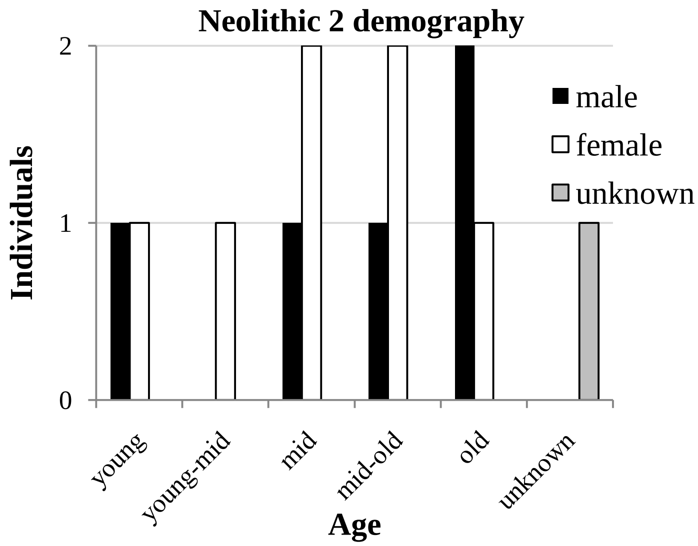


Figure 6.3: The demography of the sample taken from mortuary phase Neolithic 2

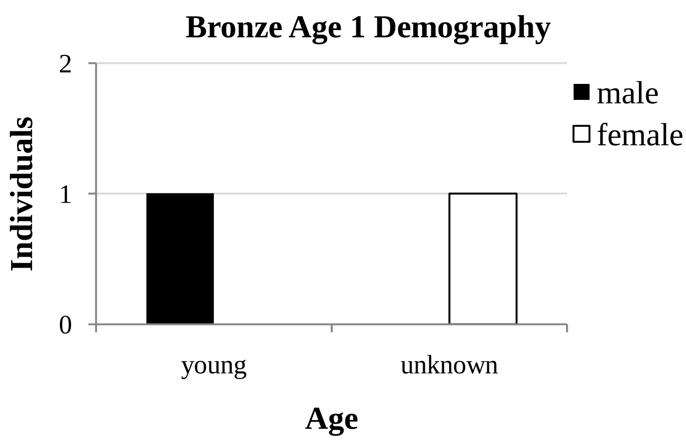


Figure 6.4: The demography of the sample taken from Bronze Age 1.

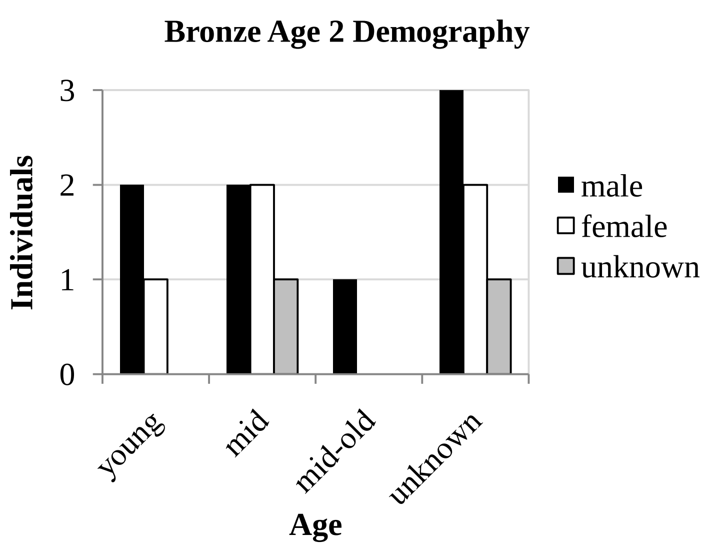


Figure 6.5: The demography of the sample taken from Bronze Age 2.

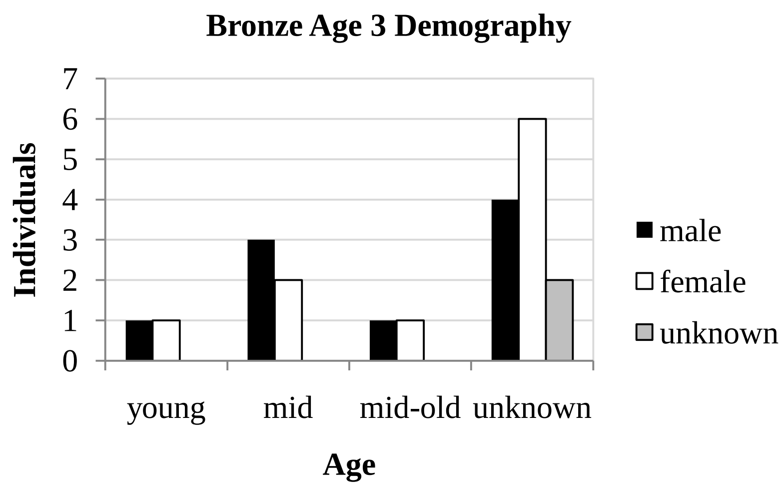


Figure 6.6: The demography of the sample taken from Bronze Age 3.

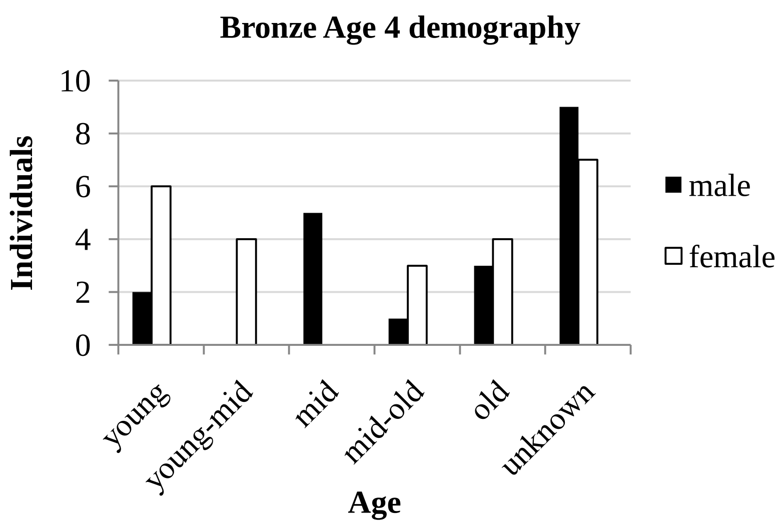


Figure 6.7: The demography of the sample taken from Bronze Age 4.

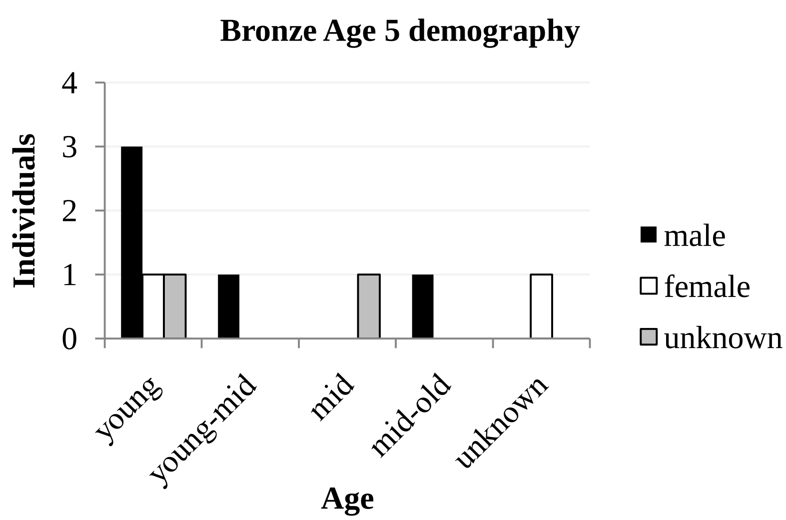


Figure 6.8: The demography of the sample taken from Bronze Age 5.

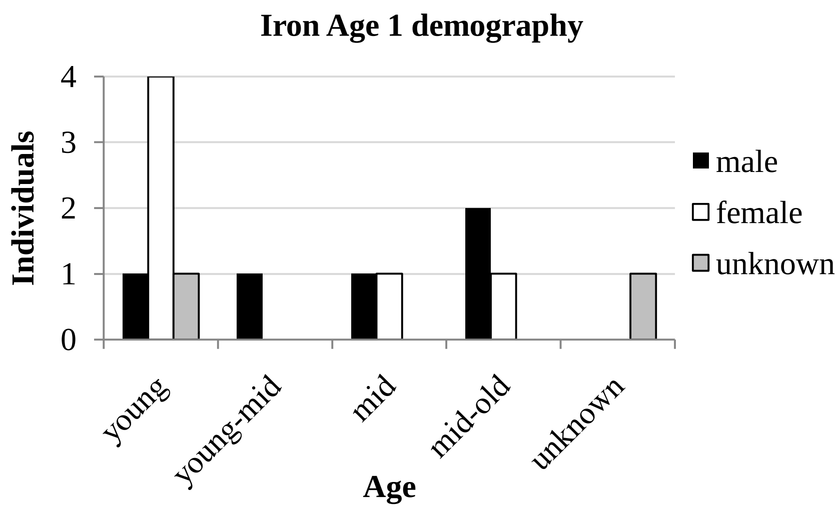


Figure 6.9: The demography of the sample taken from Iron Age 1.

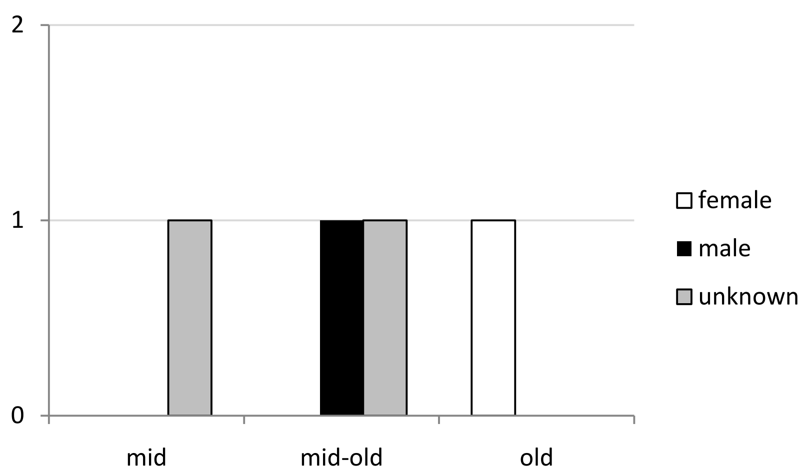


Figure 6.10: The demography of the sample taken from Iron Age 2**.**

6.3 Dental enamel Sampling

Dental enamel for isotopic analysis was collected during two sampling trips to the Fine Arts Department, Phimai where the cemetery sample of Ban Non Wat is currently housed.

Care was taken not to remove the tooth from the mandible, or take an entire loose tooth from the collection if it could be avoided. Instead enamel chips were removed *in situ* and only these small chips were removed from the collection for analysis.

Enamel chips were removed from the body of the tooth using a surgical steel scalpel inserted at the cemento-enamel junction. This plane of weakness was exploited so that the enamel could be levered away from the underlying dentine.

Preparation for isotopic analysis was then conducted at the Durham University, and methods are given in sections 7-9.

7. Isotopic Analysis

7.1 Initial sampling

Each analysis was conducted upon a chip of dental enamel weighing between 5 and 10mg. These chips were removed from the body of the tooth, scraped clean of their dentine and mechanically cleaned of particulates and calculus on their surfaces using a surgical steel scalpel.

7.2 Diagenesis

Isotopic ratios in archaeological samples may be contaminated by ions from the burial environment (Price et al., 1992; Sealy et al., 1991). These may be incorporated into the sample as pore-filling cement, adsorbed onto the surface of apatite crystals (Koch et al., 1997), or re-precipitated as non-biogenic apatite (Koch et al., 1992). This may bias isotopic ratios measured in the sample, and must be dealt with before analysis.

7.2a Diagenesis at Ban Non Wat

Previous studies have established that diagenetic change is certainly a problem at Ban Non Wat (King et al., 2011). Bone samples from the site have been extensively analysed using FTIR (fourier transform infra-red) and Ramen spectroscopy as well as LA-ICP-MS (laser ablation inductively coupled plasma mass spectrometry) and scanning electron microscopy, to reveal that collagen has been completely denatured, extensive recrystallisation of bone has occurred, and secondary minerals have formed within the inorganic matrix of the bone.

In contrast to the results gleaned from bone samples at Ban Non Wat, Ramen spectroscopy has indicated that the crystalline matrix of dental enamel was unchanged post-depositionally. Peak positions remained consistent between modern and archaeological teeth from Ban Non Wat, indicating that no foreign ions were present with the matrix. Thin section analysis also yielded no evidence of secondary mineral formation. These results are consistent with the understanding that dental enamel is less subject to diagenesis (Hoppe et al., 2003), and justify the analysis of this tissue during this study.

7.3 Removal of diagenetic components

Pre-treatment to remove diagenetic components usually takes the form of washing or leaching using weak acids. It takes advantage of the fact that there are differences in solubility between biogenic and diagenetic apatite, and attempts to dissolve the latter, while leaving the former available for analysis. In this study removal of diagenetic components was conducted on whole chips of dental enamel prior to grinding and dissolution for carbon/oxygen isotope analysis, and purification for strontium analysis.

7.3a Differences in expected level of diagenetic alteration

As mentioned in section 7.2a) diagenetic change is much more of a concern when dealing with bone or dentine samples. Bone in particular is extremely susceptible to diagenetic change because its inorganic matrix is deposited in concentric layers around organic collagen fibres. As early as three months after death microbial activity begins to undermine the structure of these Haversian systems (Bell et al., 1996), providing a plane of weakness within the bone along which secondary mineralization may occur.

Dental enamel, on the other hand, has a far more homogenised crystal lattice, comprised of tightly-packed, regular hydroxyapatite prisms with very little inorganic material present within the matrix (Hillson, 1996; LeGeros, 1981). These factors combine to make it far more resistant as a tissue to diagenetic alteration (Hoppe et al., 2003).

7.3b Methods of pre-treatment

The differences in crystallinity between bone/dentine and dental enamel mean that different methods of pre-treatment are needed depending on the tissue. Many attempts have been made to develop a protocol for removal of diagenetic components from bone and dentine (e.g. Sillen, 1986; Koch et al., 1997; Lee-Thorp & van der Merwe, 1991), but with little consensus over the best method.

Sillen (1986) advocated a 'solubility profiling' technique in which powdered samples were soaked in a buffered acid solution, ultrasonicated, rinsed, and then given a new buffered solution to remove the most soluble carbonates in the sample in progressive stages. Work by Trickett et al. (2003), however, has shown that diagenetic and biogenic apatite are far more similar in terms of their solubility than previously thought, and that even if solubility profiling was applied to bone and dentine samples the $^{87}Sr/^{86}Sr$ ratio obtained during analysis was similar to that of soil leachate from the burial site. These results differ from those of dental enamel which, although similarly unaffected by solubility profiling, seems to incorporate little diagenetic material into its crystal lattice in in the first place (Trickett et al., 2003).

Koch et al. (1997) raised the issue of organic material within the matrix, and its surface adsorbance of bicarbonate ions from the burial environment. This is a significant problem in bone, but less so in enamel which is < 2% organic material (LeGeros, 1981). Nonetheless oxidisation of organic matter in bone can be achieved by soaking in sodium hypochlorite (NaOCl), or hydrogen peroxide (H_2O_2). This followed with soaking in 1M acetic acid (CH_3COOH) has been shown to remove diagenetic apatite from the sample (Koch et al., 1997).

Balasse et al. (2002) refined this technique for dental enamel after finding that 1M acetic acid caused large net weight loss of sample. Their research refined the treatment methods, and showed that soaking in NaOCl followed by soaking in dilute acetic acid (0.1M) for only four hours retained enough sample to glean meaningful results whilst still eliminating diagenetic apatite.

7.3c Pre-treatment method used in this study

Since it is generally agreed upon that dental enamel is resistant to diagenetic change (e.g. Hoppe et al., 2003; Koch et al., 1997; Wang & Cerling, 1994), intensive pre-treatment was deemed unnecessary. In this study each sample was mechanically cleaned of surface particulates, then leached for 4 hours in 10% vol. acetic acid. The leachate was then pippetted out and the sample washed with MilliQ to ensure the dissolution of any secondary ions before drying down (cf. Koch et al., 1997; Balasse et al., 2002).

8. Strontium Isotope Analysis

8.1 Background

Strontium isotopes are fundamentally derived from the underlying geology of an area in which an individual lives or, more specifically, derives their food. Strontium occurs in the environment as ^{84}Sr, ^{86}Sr, ^{87}Sr and ^{88}Sr. These isotopes are all stable, but ^{87}Sr is also radiogenic, forming from the radioactive decay of ^{87}Rb (Rubidium). ^{86}Sr is a constant in nature and ^{87}Sr varies due to how much ^{87}Rb was initially present in the bedrock upon its crystallization, and the length of time since crystallisation i.e. how long ^{87}Rb has been decaying to ^{87}Sr for (Bentley, 2006; Montgomery, 2010). Rock types, therefore, have discrete $^{87}Sr/^{86}Sr$ ratios which are taken up through physical and biological processes into water sources, plants and animals, eventually becoming part of human skeletal and dental tissues (figure 8.1).

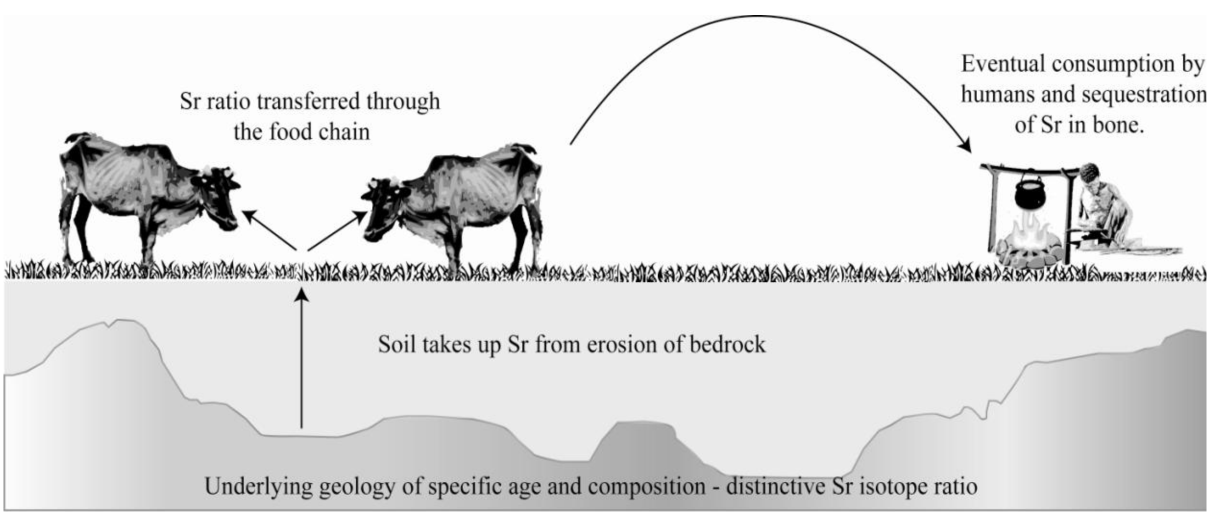


Figure 8.1: Strontium isotope ratios in the terrestrial environment.

Geological variation accounts for most of the differences in Sr isotope ratio found in inland areas, but oceans and seas are also an important sink for strontium. In the present day all seas and oceans have a Sr isotope ratio of approximately 0.7092 (e.g. McArthur et al., 2001). Seaspray, and coastal rainfall causes settlements in coastal areas to have a local Srisotoperatio which is close to this value.

The discrete strontium isotope ratios found in areas of different regional geology mean that, in principle, if an individual has spent their infancy in a certain area, and in later life migrates to an area of different geology their tooth enamel (which forms during infancy) will retain the strontium signature of their childhood home, and they will identifiable as a migrant (Beard and Johnson, 2000).

8.1a How does Strontium become incorporated into human dental and skeletal tissues?

The human skeleton is composed of an organic portion (collagen) and inorganic portion. The inorganic portion of bone is essentially composed of the mineral hydroxyapatite ($Ca_5(PO_4,CO_3)_3OH$), and is the body's most important sink for calcium. Strontium shares many chemical properties with calcium as it has the same valency (2+) and is the alkali earth metal closest to it in size. Since strontium behaves like calcium it is often substituted for it in the tetrahedral position of hydroxyapatite, by the body during nutrient uptake and internal distribution (Montgomery, 2010). Strontium is distributed relatively homogeneously throughout the body, though bone and dentine usually contain more that enamel (Montogomery, 2010; Parker & Toots, 1980).

The amount of strontium in total which is taken up by the body is dependent on a number of factors, of which diet is perhaps the most important. There is a progressive selection against Sr^{2+} in favour of Ca^{2+} as the trophic level of the organism increases, and Sr uptake is also suppressed in Ca or protein rich diets (Burton and Wright, 1995). Conversely Sr uptake increases with high fibre (i.e. herbivorous) diets. These factors mean that Sr concentration in the body is at least partially dependant on diet, and that the plant part of the diet is more likely to be the dominant contributor to skeletal Sr signature than the animal part (Burton and Wright, 1995; Burton, 2008).

In fact, although in studies of migration we often assume that strontium isotope fractionation is negligible, and ratios are transmitted almost unchanged from underlying geology into the environment, there are processes which cause their fractionation (Knudson et al., 2010). These are primarily based on the differences in mass between the isotopes, with lighter isotopes preferentially incorporated into physical and metabolic reactions (Knudson et al., 2010). Mass dependent strontium fractionation is well known in the geological literature, and appears to be strongly temperature dependent (e.g. Fietzke & Eisenhauer, 2006), but these effects are not usually considered in archaeology. This is because the primary use of strontium isotopes in archaeology is as indicators of mobility in the past. In mobility studies fractionation effects are corrected for by normalizing $^{86}Sr/^{88}Sr$ to the constant value of 0.1194 (Steiger & Jäger, 1977), in order that strontium isotope ratios may reflect those of the bedrock.

The fractionation of Sr is important though, and has paved the way for strontium isotope ratios to be used in many new and exciting ways. The temperature dependence of fractionation, for instance, means that strontium isotopes can be used as a form of paleothermometer, to indicate the conditions under which calcium-based organisms such as corals were forming (Rüggeberg et al., 2008). The trophic level fractionations of Sr due to metabolic processes has also led Knudson et al. (2010) to propose that $^{88/86}Sr$ may be used as a paleodietary indicator.

It has been shown that organisms preferentially incorporate lighter ^{86}Sr into tissues, and this isotope gets more concentrated in higher trophic levels, causing $^{88/86}Sr$ to become lower (Knudson et al., 2010). This technique has important applications for mobility studies, as the accuracy of using $^{87/86}Sr$ as an indicator of birthplace relies on the individual having sourced their food from the region (Bentley, 2006), thus independent knowledge of diet is required. In this study we use carbon isotope ratios in dental enamel for this purpose. It would, however, be preferable to establish the source of strontium in the diet using strontium itself (Knudson et al., 2010). This technique still requires much refining before it comes into common usage, but its potentials are clear.

Sr isotope analysis usually uses samples of dental enamel because it is more mineralised than either bone or dentine, and is considered less susceptible to diagenetic change after burial (Wang & Cerling, 1994; Budd et al., 2000; Nielsen-Marsh and Hedges 2000; Price et al. 2002; Montgomery, 2010). Enamel is acelleular and avascular, which means it neither regenerates nor remodels (Montgomery, 2010; Hillson, 1996). At the time of mineralisation, therefore, an individual's enamel contains strontium isotopes in a specific ratio reflecting a weighted average of those present in the food and drink they have ingested. Put simply this means that the strontium incorporated into a tooth provides insight into a slice of time during the individual's childhood (the time of initial mineralization).

8.2 Enamel formation and dental microstructure

In order to understand what strontium isotope ratios mean it is necessary to have an understanding of how the dental enamel containing them is structured. Enamel is formed by cells called ameloblasts which secrete apatite crystallites in ‘tracks’ to form a matrix (Hillson, 1996). Enamel secretion follows a ciracadian rhythm resulting in cross-striations across a prismatic structure. Long-scale incremental structures called ‘Striae of Retzius’ are also present within a tooth and represent the successive positions of the front of enamel formation (Scott & Turner, 2000). When these striae contact the enamel surface they form rings around the circumference of the tooth known as perikymata. Calculations of the periodicity of striae of Retzius formation from cross-striations indicates that they are formed on average once every 8 days (Hillson, 1996). These microstructural elements of the tooth are represented graphically on figure 8.2.

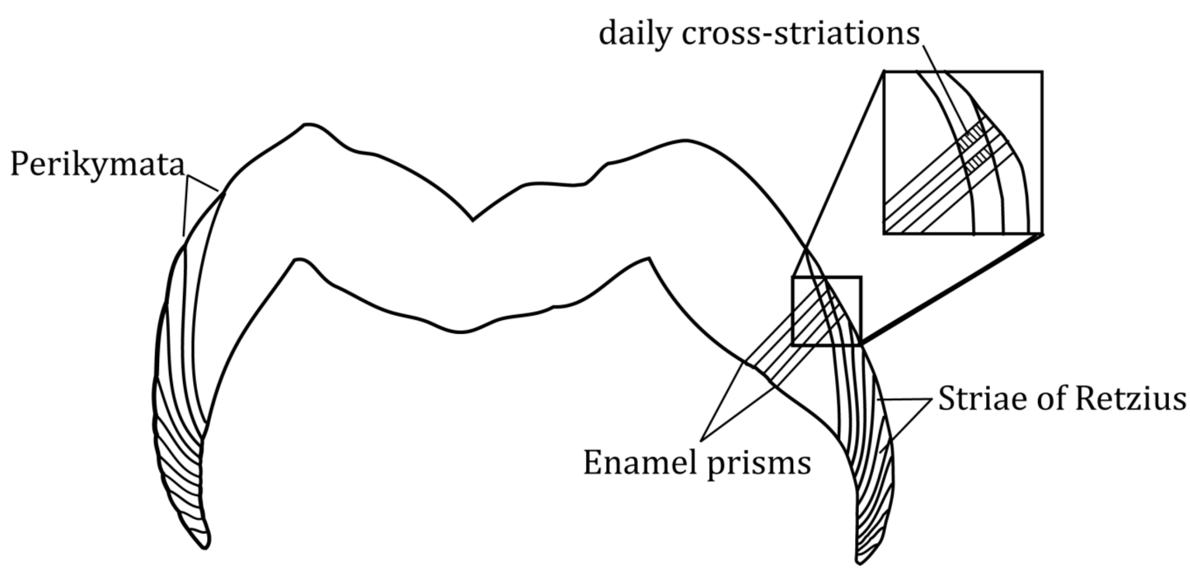


Figure 8.2: Dental **e**namel microstructure, after Smith et al. (2003)

The organic matrix of dental enamel is secreted over a period of 70-80 days (Dean, 2009), and maturation of the enamel, that is the removal of organic material from the matrix, takes several years (Hillson, 1996; Shellis, 1998). This means that variation in the isotopes incorporated into a tooth is very possible. The incremental nature of structures, such as striae of Retzius, means it is possible to target certain areas of a tooth which represent different periods of development. This can be very useful to the archaeologist wanting to investigate issues which require fine-scale resolution of time e.g. movement during childhood (Richards et al., 2008), or weaning processes (e.g. Humphrey et al., 2008). Techniques such as LA-ICP-MS or microsampling prior to TIMS analysis can be used to target specific areas of the enamel for these purposes. There is debate over the accuracy of LA-ICP-MS analysis of isotopic ratios (see Nowell & Horstwood, 2009 and section 8.8 for further discussion), but if this is resolved it is likely to become a useful tool.

While fine-scale resolution of mobility would be ideal when looking at any archaeological population, at present the techniques which would allow this kind of analysis remain costly. Added to this is the problem that dental microstructure is not fully understood, and so interpretation of results remains problematic. In this study fine-scale resolution of isotopic variation is not necessary, as the aim is to identify broad patterns of *if* individuals have moved, rather than more specific questions of *when*. In order to avoid the problems of heterogeneity within dental enamel, bulk samples were taken (i.e. large chips of enamel) effectively homogenizing any variation which may be present on a finer-scale.

8.3 Biopurificiation

It is also important to note that strontium may be circulating in the body for months or even years before it is incorporated into the body's tissues. In reality then the ratios found in teeth may be an 'average' formed of all the strontium ingested up to that point, this is especially true if bulk samples are taken (Montogomery, 2010). If an individual moves during the period of mineralisation this may not be visible isotopically. This averaging process is known as biopurification, and while it may hamper the identification of migrants in some circumstances, it undoubtably proves useful to the archaeologist in terms of its removal of seasonal variation in food source exploitation (Montgomery, 2010).

The process of biopurification is something of a lifeline to archaeologists interested in using Sr isotopes as indicators of mobility. There is a great deal of heterogeneity in terms of biologically available strontium in any environment (Sillen et al., 1998). This variation means that without an averaging process being in place it would be impossible to distinguish different substrates based on the plants/animals raised on them.

Work by Burton (Burton et al., 1999; Burton et al., 2003) revealed that organisms will preferentially incorporate calcium over strontium into the body's tissues, meaning that only 10-40% of strontium ingested by mammals is absorbed and retained in the body's tissues (Bentley, 2006). This reduces variance in strontium/calcium ratios up the food chain (figure 8.3), and by extension results in extremely homogeneous strontium isotope ratios in humans from the same geological terrain.

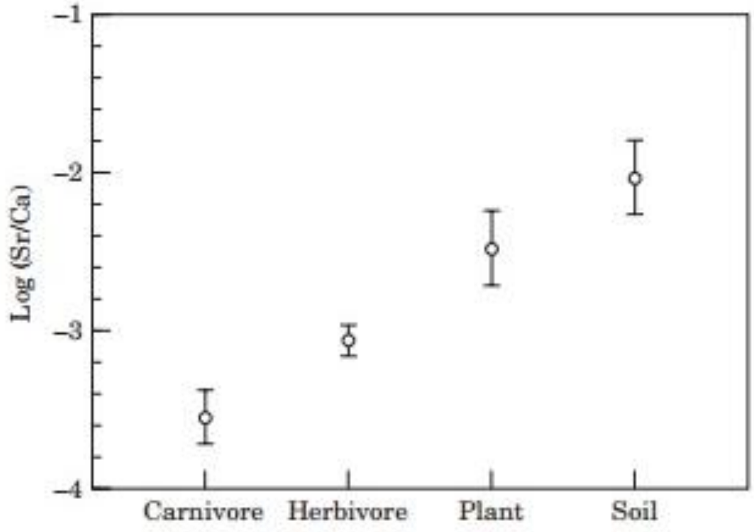


Figure 8.3: The biopurification of strontium in the environment. From Burton et al. (1999).

Biopurification has been studied extensively in numerous food-webs following Burton's work. Blum et al. (2000), for instance, have measure both Sr/Ca concentrations and $^{87}Sr/^{86}Sr$ within the same food web to show that $^{87}Sr/^{86}Sr$ in organisms was relatively homogeneous, accurately reflecting the mixing of different strontium sources in the environment, while Sr/Ca show a systematic trend to lower ratios in higher trophic levels.

8.4 Provenancing Individuals using Strontium Isotope Ratios

The use of strontium isotopes in archaeology has grown dramatically since its first suggestion by Ericson (1985), primarily because of its potential to definitively identify the movement of peoples and cultures across a landscape. Initially the suggestion was that life histories could be derived from a single skeleton by comparing the strontium isotope ratios found in bones which reflect the strontium sourced just prior to death, with the ratios in dental enamel, reflecting childhood (Price, 1994). Some studies do still attempt this (e.g. Price et al., 2000), but it is now recognized that most burial conditions do not preserve isotope ratios in bone as they were in life (e.g. Chiaradia et al., 2003; Budd et al., 2000). This is certainly the case in sub-tropical Thailand, where seasonal inundation of burials has caused dissolution and recrystallization of much of the bone (King et al., 2011; Bentley et al., 2005). As a general rule strontium isotope analysis is restricted to dental enamel, and in some cases dentine, in archaeological samples, with this technique having great potential to shed light on prehistoric mobility.

The potential of strontium isotope analysis to identify migrants means that the archaeologist is rarely content to merely identify non-local individuals, instead they wish to know *where* they came from so as to better interpret processes in prehistory. This, however, is often impossible. Strontium isotope ratios provide a useful tool in provenancing individuals, but they cannot provide all of the answers.

For the technique to be effective it requires that migratory individuals have come from a place of measurably different geology, giving them an obviously different isotopic ratio to local individuals. This is not always the case as humans tend to seek out the familiar, and so when migrating may deliberately choose to reinstate themselves in an area of similar underlying geology and terrain type (Bentley, 2006). Even for those individuals who have moved from an area of entirely different geology, it is unlikely that their place of origin is the only place with their specific strontium isotope ratio. When strontium isotopes do indicate migration has occurred all the archaeologist can do is give possible regions of origin for the individual based on isotope ratio, and offer an interpretation of the most likely based on other archaeological evidence available.

Added to these problems is the complexity of the strontium isotope system even within the local area. There is rarely just one source of strontium in an environment. Instead the ratio of $^{87}Sr/^{86}Sr$ in the body is a complex mixture reflecting the strontium ratios and concentrations in different bedrocks, the rate of erosion of these strontium sources, atmospheric strontium, the water source used by the individual, proximity to the ocean, and subsistence strategy (Bentley, 2006). As previously mentioned (section 8.3), biopurification does much to simplify this, but in order to more accurately interpret results modeling of the strontium isotope system is often necessary.

8.5 Mixing models in strontium isotope geochemistry

If an individual sources their food from multiple different geological terrains the isotope ratios from each of these sources are mixed. Variation in rainfall can also cause mixed signals, as rain can have a variable strontium isotope ratio depending on how much is sourced from seawater, and how much from local bodies of freshwater. This means the strontium isotope ratios in individuals using multiple food and water sources may not reflect the geology upon which they are living, but instead fall somewhere along a mixing line representing the different sources (Montgomery et al., 2007).

This mixing of strontium sources means that there is the potential for both false positives and false negatives in migratory studies. For instance, a non-migrant individual may be identified as a migrant if they source their food from different locations, or the level of rainfall either increased or decreased during the period of their enamel mineralisation, causing them to have significantly different $^{87}Sr/^{86}Sr$ isotope ratios (Montgomery, 2010).

Mixing models can be used to deal with these problems. This technique involves drawing mixing lines between two end-member geologies, in order to establish where individuals fall and whether or not it is plausible that their isotopic ratios could be caused by mixing of these sources. It has been used by Montgomery (2010) to show that use of different geological terrains for different aspects of the diet (e.g. granitic terrains for grazing animals and basaltic for growing crops) could lead to isotopic ratios in local people that superficially might indicate a region of origin on a different rock type altogether. This highlights the need to understand the underlying geology, particularly if multiple geologies are present within a single area. Knowledge of which land is best suited to agriculture will be essential in interpreting isotopic results in these regions.

Bentley et al. (2003) employ a similar technique, calculating the effects of different inputs of food resources grown/raised in different terrains on overall isotopic ratio. Their work revealed that small-scale supplementation of an agricultural diet with wild foods would change isotope signatures, but not enough to make individuals appear non-local. More large-scale foraging activity, however, may lead to local individuals being interpreted as migrants if food is sourced from multiple terrains. This highlights the importance of having a basic knowledge of subsistence strategy and the local geology in any area where strontium isotope analysis is to be applied.

Schweissing & Grupe (2003) have also used mixing lines in interpreting isotopic results to assess the origins of 'non-local' individuals, defined by differences of more than 0.001 between tooth and bone isotope ratios. In this study mixing lines were between pure carbonate and pure granite endmembers, with carbonate being the local rock type, and a nearby granitic terrain considered the most likely source of migrants. The fact that all outlying individuals fell within this mixing band was then used as evidence for the origins of migrants being in the granitic terrain.

8.6 Biologically Available Strontium

An alternative, or sometimes additional, method of dealing with the complexity of the strontium isotope system is to use a proxy for the biologically available strontium in a given area. An average local signature of biologically available strontium may be obtained by analysing the strontium isotope ratios present in local mammals. Mammals eat a mixture of plant and animal food sources from a single area, effectively homogenizing the strontium signal (Price et al., 2002). This means that the Sr isotope ratios within their skeletal tissues are a useful proxy for the strontium in the diet of humans. This is particularly true of the pig (*Sus scrofa).*

In Southeast Asia the pig has been kept as a domesticate for thousands of years, and zooarchaeological evidence suggests the pig was kept within, or close to, prehistoric settlements, and not allowed to range (e.g. Higham & Kijngam, 2009). Its diet often comprises of the bi-products or waste from human consumption, this makes it an excellent indicator of the local signature which should be found in the human population. This being the case, much of the material run initially in this study was archaeological pig enamel. These first analyses both allowed familiarisation with the techniques used in isotopic analysis and also gave insight into the variability of the biologically available strontium within the Upper Mun River Valley.

8.7 *Strontium isotopes in the Upper Mun River Valley*

In order to predict typical 'local' Sr isotope signatures for the Upper Mun River Valley the geology of the region must be considered. Broadly speaking the geology of the Mun River Valley is different to the geology of the rest of the Southeast Asian peninsula (figure 8.4), indicating that strontium isotope ratios should of use in identifying long-distance migrants.

Unfortunately this simplicity is merely superficial. If strontium isotope ratios are looked at on a finer scale, for instance only within the Khorat Plateau and the Upper Mun River Valley catchment (figure 8.5), it becomes obvious both that there are multiple geological terrains contributing to the biologically available strontium in the region, and that these terrains extend over a wide area. This means that the local isotopic signature is likely to fall along a mixing line for these terrains, and most of the UMRV and surrounding area will have very similar isotopic ratios.

The soils of the Mun River valley have strontium isotope signatures reflecting mixing of strontium from the different formations of the local bedrock, which crop out and are eroded by the Mun River. The local bedrock is primarily composed of the Khorat group, which is Mesozoic red arkose sandstones, grey sandstones, siltstones and shales. The many different rock types associated with the formation means it does not have a single, homogeneous, strontium isotope ratio which can be said to represent the whole formation. Also worth noting are the small basaltic outcrops present within the local geology.

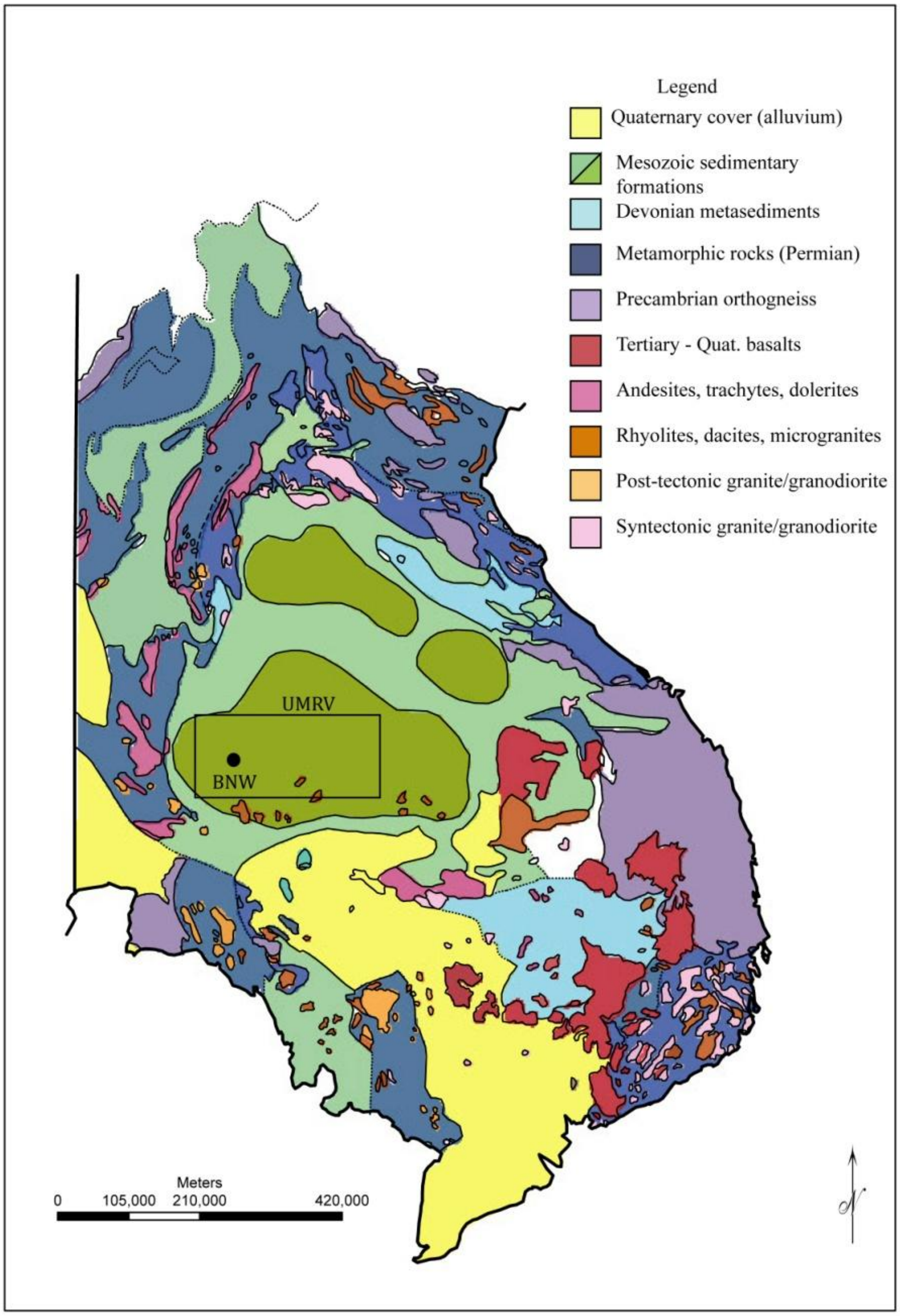


Figure 8.4: The broad-scale geology of the Southeast Asian peninsula. Ban Non Wat (BNW) and the Upper Mun River Valley (UMRV) marked. Information from Beckinsale et al. (1979), Zhou and Mukasa (1997), Charusiri et al. (2006), and Timofeeff et al. (2006).

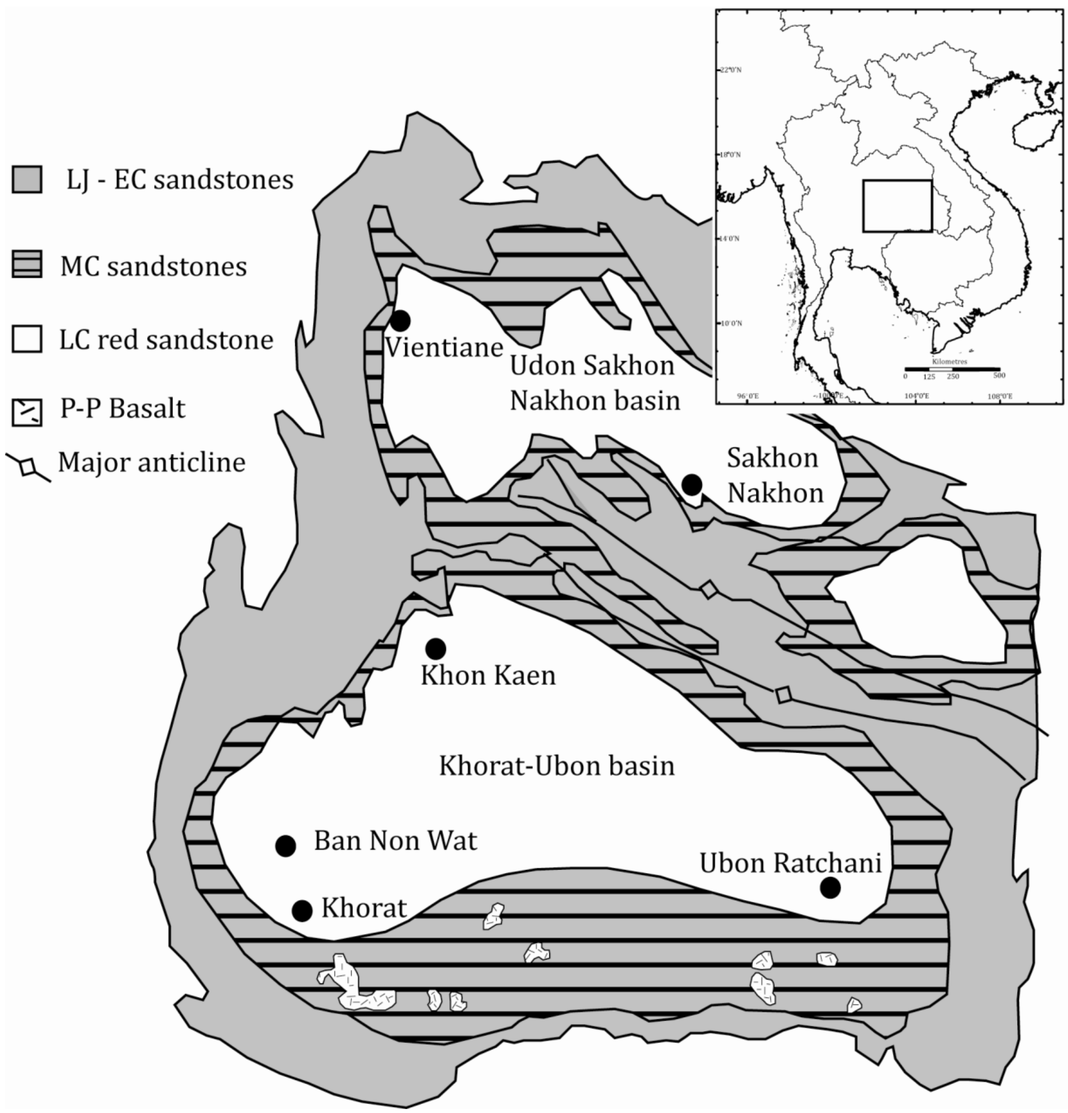


Figure 8.5: The geology of the Khorat Plateau and surrounding area, after Charusiri et al. (2006). LJ – Late Jurassic, EC = early Cretaceous, MC = Middle Cretaceous, LC = late Cretaceous, P-P = Plio-Pleistocene.

Typical Sr ratios for the rock types occurring closest to Ban Non Wat are presented in table 8.1.

Formation/rock type	**Expected/measured Sr isotope ratios (whole rock samples)**	**Source**
Maha Sarakham evaporites	0.70712-0.7075.	Timofeeff et al. (2006) El Tabakh et al. (2003)
Red sandstones – Khorat group	~ 0.710	Bentley et al. (2009b)
Nakhon Ratchasima Basalt	0.70354-0.70388	Zhou & Mukasa (1997)

Table 8.1: Rock types found close to Ban Non Wat and the $^{87}Sr/^{86}Sr$ typical for them.

8.8 Column Chemistry Methods

8.8a Justification for use of techniques

There are several possible methods of strontium isotope analysis, in this study strontium was purified using column chemistry prior to analysis using MC-ICP-MS (multi-collector inductively-coupled-plasma mass-spectrometry). Other methods include analysis by TIMS (thermal ionization mass spectrometry) and use of LA-ICP-MS (laser-ablation ICP-MS).

Both TIMS and MC-ICP-MS analyses involve purifying strontium from dissolved dental enamel samples prior to analysis. This can be achieved either through liquid chromatography (Vroon et al., 2008), or column chemistry (Charlier et al., 2006). In this study column chemistry methods were used, as this is the protocol in place at the Northern Centre for Elemental and Isotopic Tracing, where research was conducted.

The purification of strontium prior to analysis means that *in situ* analysis of dental enamel is impossible i.e. a specific area of the tooth cannot be targeted for analysis unless it is microsampled before dissolution. Purification techniques are usually relatively time-consuming and require attention to cleanliness to avoid contamination of the sample.

LA-ICP-MS on the other hand has the advantage that it can be used to look at variation across a tooth by ablating different areas depending on the focus of analysis. Small-scale variations within teeth may relate to developmental processes or mobility, and their recognition may be significant. LA-ICP-MS analyses do not involve purification prior to mass spectrometry and so are comparatively very quick. Superficially then LA-ICP-MS seems the preferable technique.

While analysis using LA-ICP-MS is indeed quicker, and does retain spatial data, there are numerous studies which question the accuracy of results obtained through LA-ICP-MS. This is because there is no purification step and elements or molecules which may cause mass interferences interference (e.g.^{87}Rb, ^{86}Kr, iron oxides, calcium dimers) are analysed alongside strontium isotopes (Vroon et al., 2008; Jackson & Hart, 2006; Woodhead et al., 2005). In order to obtain accurate results calibrations for these interferences must be carefully thought out and applied to the data. More traditional techniques do not have this problem due to purification prior to analysis and results are far easier to interpret.

In their study of LA-ICP-MS data reported by Richards et al. (2008), Nowell & Horstwood (2009) show how sensitive to calibration LA-ICP-MS results are by using subtly different corrections to give diametrically opposed results. They highlight the need for calibrations to be conducted in real-time in order to change according to the elements present within the specific sample which may cause interferences. It is also apparent that corrections based on constant strontium concentrations are invalid, as strontium does not substitute into the enamel matrix in a homogeneous manner (Simonetti et al., 2008).

In addition to these mass interferences there are also fractionation effects induced by the processes of laser ablation and mass spectrometry, which must be corrected for (Vroon et al., 2008). Fractionations during mass spectrometry are routinely corrected for by normalizing to the constant $^{86}/^{88}$Sr ratio found in nature. It is usually assumed that the fractionations induced by laser ablation are the same as those in mass spectrometry, but a recent study by Jackson and Hart (2006) indicates this may not be the case.

The complicated calibrations and deep understanding of mass bias and isobaric interferences required to glean accurate LA-ICP-MS results, mean it is a far more complex technique to use. It is also likely to be less precise as currently the best way to calibrate results is not agreed upon. In this study spatial resolution within the tooth is not necessary, and it is preferable to use bulk samples of enamel in order to homogenize any potential isotopic heterogeneity (Nowell & Horstwood, 2009). The focus here is not on short-term variation in strontium but instead broad-scale patterns. For this reason MC-ICP-MS analysis is used in preference to LA-ICP-MS. This means that analysis here does involve more preparation steps, but actual analysis is easier.

8.8b Method of Sample dissolution

Tooth samples were dissolved in 500µl 16N HNO_3 on a hotplate (at 90ºC) for one hour. Excess HNO_3 was then removed through evaporation, and the sample dried down on the hotplate (at 120ºC). 400µl of 3N HNO_3 was then added to the residue and the sample re-dissolved. This repeated dissolution ensured that the final solution was clear and free of precipitates.

8.8c Method of Column chemistry

Strontium columns were prepared in advance, made up of a standard 1ml pipette tip, fitted with a circular piece of polypropylene frit at the dropper end. The tip of the pipette was cut away on a diagonal beneath the frit to allow efficient emptying of the column (Charlier et al., 2006).

Before loading with Sr spec resin the column was washed with one column volume of 6N HCl, then 2 column volumes of MilliQ water. 100µl Sr spec™ resin was then loaded into the column.

Sr spec™ resin (Eichrom Technologies, 2010) is used to purify strontium from the solution. This resin has a high affinity for strontium, and its tendency to bond with Sr increases with nitric acid concentration (figure 8.6). This means that when the column is nitrified Sr is retained within the resin, and other elements are eluted. When the concentration of nitric acid is lowered through the addition of MilliQ Sr is no longer retained by the resin and is allowed to pass through the column.

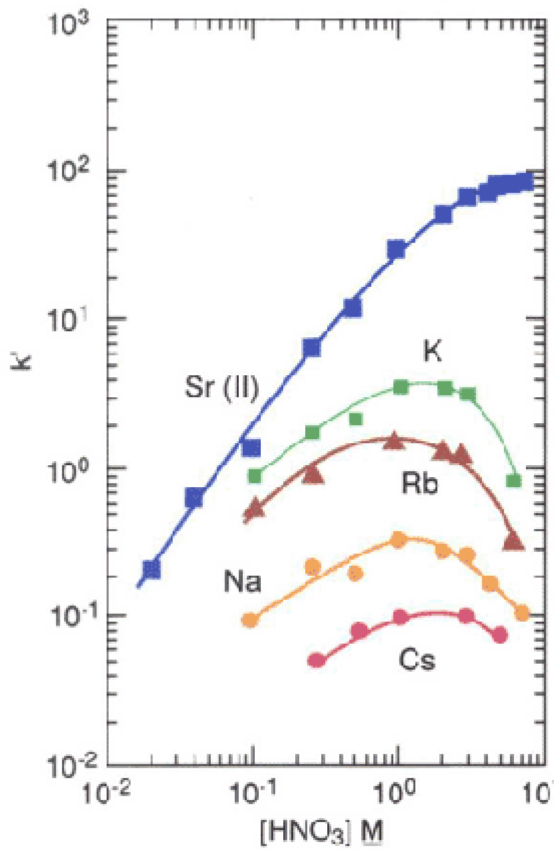


Figure 8.6: The acid dependency of various ions with Sr spec resin (after Horwitz et al., 1991)

Impurities were removed from the column by washing with one column volume 6N HCl followed by one column volume MilliQ. The column was then converted to a nitric acid environment by the addition of two 100µl aliquots of 3N HNO_3.

The sample to be analysed was then loaded using a pipette, ensuring the tip did not touch the edge of the column and introduce contamination. This was then washed through the column by adding a further two 200µl aliquots of 3N HNO_3. At this stage of the process, in a nitric acid medium, the Sr Spec resin binds to Sr ions, but allows others including Rb and Ca to pass through into the waste beakers placed under the columns.

Waste beakers were then replaced with collection beakers beneath the columns, and the columns were washed with two 250µl aliquots of MilliQ. This reduces the acidity of the environment and causes the Sr spec resin to break its bonds with the strontium ions, releasing the strontium from the sample, into the collection beakers.

Columns were discarded after use, and beakers thoroughly cleaned using a multi-day cleaning procedure involving both acid and MilliQ washes. This removes the possibility of contamination from previous batches of column chemistry.

8.8d Procedural Blanks

In order to ensure that contamination of the sample is not occurring during column chemistry, procedural blanks were prepared and analysed alongside samples. At least two procedural blanks were included in each batch of column chemistry. In order for results to be valid the amount of Sr in blanks should be < 1% of the sample's Sr concentration (Charlier et al., 2006). In dental enamel this is not difficult as teeth are abundant in Sr, much more so than geological samples. For work with dental enamel blanks should be under 1000pg Sr concentration, to ensure contamination does not affect results. If blanks exceed this in a uniform pattern then blank corrections can be applied to the sample. In this study no procedural blanks exceeded 75pg of strontium, and average blank Sr concentration was 29pg, meaning that corrections did not need to be applied and contamination was not an issue.

8.9 Multi-Collector Inductively-Coupled-Plasma Mass-Spectrometry (MC-ICP-MS)

Purified strontium was analysed for $^{87}Sr/^{86}Sr$ ratio using a ThermoFisher Neptune plasma ionisation MC-ICP-MS at the Northern Centre for Isotopic and Elemental Tracing, Durham University. Solutions were diluted using 3% HNO_3 to allow measurement of Sr at a beam size of 20V. $^{87}Sr/^{86}Sr$ was normalised using repeated measurements of the NBS 987 standard ($^{87}Sr/^{86}Sr$ = 0.710240). Analysis was conducted in 10 batches, with standard averages reported for each of these batches in table 1, appendix 2.

9. Carbon and Oxygen Isotope Analysis

"You will die but the carbon will not; its career does not end with you."

Jacob Bronowski, The Ascent of Man (BBC)

9.1 Carbon Isotope Ratios

Dietary carbon isotope analysis measures the ratio of ^{13}C to ^{12}C in a sample and reports it relative to the established ratio found within a specific standard, here PDB (Pee Dee Belemnite Limestone), to give an overall result in parts per thousand (‰). This process is given in equation 1 (below). While PDB was not run as the actual standard during this analysis, instead internal standard DCS01 was used, this was calibrated to the known value of PDB in order to maintain consistency with previously published results.

Equation 1: Calculation of $\delta^{13}C$

$$\delta = \left[\frac{\left[\frac{^{13}C}{^{12}C}\right] sample}{\left[\frac{^{13}C}{^{12}C}\right] PDB} - 1 \right] 1000$$

Broadly speaking $\delta^{13}C$ in human tissue reflects the diet of the individual. It can be used to differentiate between C_3 and C_4 plant food sources, as well as terrestrial and marine input to the diet. The background to the technique, expected ratios in the UMRV, and methods of analysis are detailed in the following sections.

9.2 *Carbon isotope fractionation in plants*

Carbon isotopes are incorporated into plants through photosynthesis, a method of converting the carbon dioxide in air into sugars. There are two main photosynthetic pathways the Calvin-Benson and the Hatch-Slack pathway (see Lee-Thorp, 2008 for a review). C_3 plants use the Calvin-Benson pathway, creating a three carbon sugar ($C_3H_6O_3$) (Calvin & Benson, 1948). This method of fixation favours ^{12}C, meaning that C_3 plants have more negative carbon isotope values than their C_4 counterparts (Lee-Thorp, 2008). C_3 plants occur in regions where fresh water vapour is abundant, they are unable to cope with decreasing CO_2 in the atmosphere as this seriously reduces their photosynthetic potential (Flexas & Medrano, 2002) they are therefore not found in arid areas. Rice is the most economically important C_3 plant in Southeast Asia, both today and during prehistory. Other C_3 food sources used in the area include legumes and fruits (King, 2006).

C_4 plants, on the other hand have developed a method of photosynthesis which is efficient in hot, dry environments with low atmospheric CO_2 (Osbourne & Beerling, 2006). They photosynthesise using the Hatch-Slack pathway, which creates a four carbon sugar ($C_4H_8O_4$) (Hatch & Slack, 1966). C_4 plants include some of the world's most valuable cereal crops such as maize and millet making their presence in the archaeological record often very significant.

There is also a third photosynthetic pathway known as CAM (Crassulacean Acid Metabolism). These plants can use either C_3 or C_4 pathways depending on the availability of sunlight and atmospheric carbon dioxide (Troughton et al., 1974). They are, however, found in semi-deserts, deserts and savannas and are unlikely to be relevant to a discussion of diet in sub-tropical Southeast Asia (King, 2006).

9.3 Trophic level and carbon isotope ratio

Organisms partition carbon isotopes into different tissues, meaning that different macronutrients from the same organism may have isotopic ratio differences of up to 2‰ (O'Leary, 1995). Fats, for instance are isotopically lighter than proteins or carbohydrates (DeNiro & Epstein, 1978). This means that carbon isotope ratios will change according to trophic level, as different macronutrients play different roles at each trophic level (Lee-Thorp et al., 1989). A carnivore, for instance has a far greater dependence on protein for both growth and energy than a herbivore, which uses more carbohydrate (Kruegar & Sullivan, 1984).

It appears that ^{13}C is enriched by approximately 1-2‰ with each trophic level increase in the foodchain (DeNiro & Epstein, 1978; Lee-Thorp, 2008). Therefore a human diet involving higher levels of meat consumption will result in less negative carbon isotope ratios than is found in those primarily using plant food sources.

9.4 Carbon isotopes in marine systems

There is a fundamental 7‰ difference between oceanic and terrestrial carbon sources; in the marine environment carbon is in the form of bicarbonate (HCO_3^-), whilst in the atmosphere it is carbon dioxide (CO_2). Carbon is more oxidized in the oceanic form, and more oxidized forms of carbon tends to concentrate ^{13}C (Craig, 1953).

Marine phytoplankton fractionate oceanic bicarbonate to roughly the same extent as C_3 plants, and higher trophic levels do further fractionate this carbon, but the level of fractionation does not vary between species (Chisholm et al., 1983). This means that the 7‰ difference between marine and terrestrial food sources is preserved and humans with a marine subsistence strategy will have substantially less negative $\delta^{13}C$ values than those using C_3terrestrial resources.

Unfortunately the carbon isotope ratios typical of marine resources can easily be confused with C_4 resource use, as they fall within the same range (Chisholm et al., 1982; Gannes et al., 1998), for this reason it is important to consider the archaeological context of any burials, and evaluate whether more positive $\delta^{13}C$ values are likely to be due to marine or C_4 resource use. In Paleolithic Europe, for instance C_4 crops simply did not exist, allowing more positive $\delta^{13}C$ to be easily interpreted as evidence for marine resource use (Stevens & Hedges, 2004; Richards et al., 2001). Conversely landlocked areas are unlikely to have had access to marine resources and so positive shifts in these areas are likely due to C_4 crop use.

9.5 Secondary effects on $\delta^{13}C$ in plants

While major differences in carbon isotope ratio can be accounted for by photosynthetic pathway, or terrestrial vs. marine differences, there are a number of other factors which influence $\delta^{13}C$. Climate has been shown by numerous studies to have an impact on the carbon isotope ratios found in plants (van Klinken et al., 2001; Heaton, 1999). This is because the isotopic fractionation in plants is dependent on stomatal conductance and carboxylation rates, both of which are affected by light levels, temperature and water availability. In fact it appears that climatic variation, not changes in diet, account for many of the isotopic differences observed in Holocene Europe (van Klinken et al., 1994; 2001).

Perhaps the most significant secondary effect in paleodietary studies is the canopy effect. There is a vertical gradient in $\delta^{13}C$ in any forest environment, with ratios in plants increasing by up to 4‰ from ground level to the top of the canopy (Broadmeadow & Griffiths, 1993), the reasons for this are not fully understood but it is hypothesized it may be due to reassimilation of ^{13}C depleted carbon dioxide by lower level plants (Dawson et al., 2002; Bonal et al., 2000). These canopy effects also cause significant differences in the $\delta^{13}C$ between forest plants and those which are free-standing or in open areas (Heaton, 1999; Krigbaum, 2005) based on light levels and the effect this has on carbon dioxide concentration (figure 9.1).

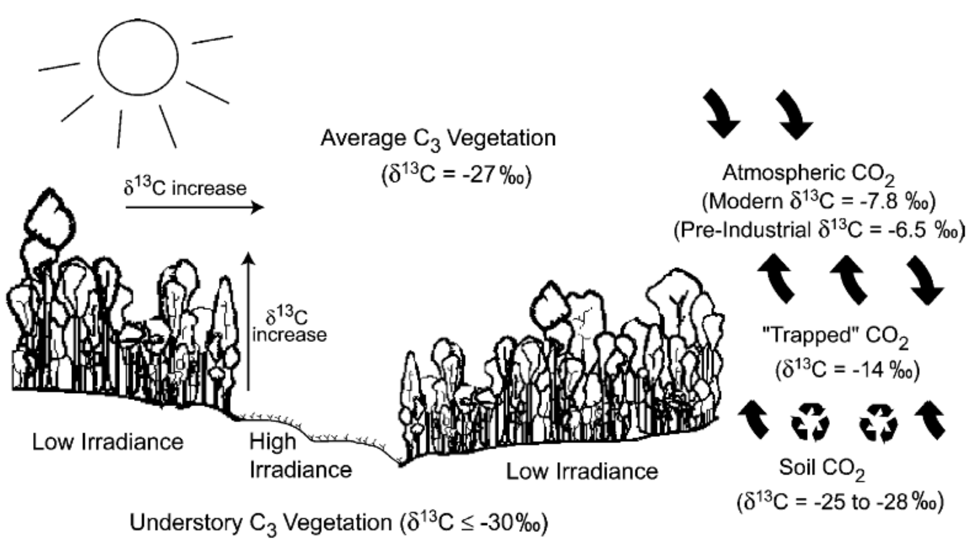


Figure 9.1: Changes in $\delta^{13}C$ relating to canopy effects. From Krigbaum (2003).

The differences between $\delta^{13}C$ in closed-canopy forests and more open environments mean that carbon isotope ratios also have the potential to be used in understanding the kinds of environments exploited by past societies. This theory has been used by Krigbaum (2003) in his study of Neolithic subsistence strategies in Borneo to show differences in environment exploited by hunter-gatherers at different cave sites. This also highlights the importance of considering the paleoenvironment when interpreting carbon isotope results in archaeology.

9.6 Carbon isotopes in human skeletal/dental tissues

Carbon isotope ratios are usually analysed using either the collagen fibres of bones and dentine, or in the carbonate of dental enamel. In this study carbon isotopes in human enamel carbonate are measured, reflecting the diet during the period of childhood in which mineralization occurred.

The average $\delta^{13}C$ across a whole organism is very close to that of its dietary intake, but on a finer scale there is a level of partitioning of carbon isotopes, with carbon from different aspects of the diet routed to different tissues (DeNiro & Epstein, 1978). Dietary protein carbon isotopes, for example, have a close relationship with those found in collagen due to the body's preference for using dietary amino acids in collagen construction (Ambrose and Norr 1993; Lee-Thorp, 2008).

Carbon isotope ratios in dental enamel, by contrast, are more reflective of the whole diet. Dental enamel carbonate is formed in equilibrium with blood bicarbonate, which in turn has the same $\delta^{13}C$ value as the 'energy' aspect of the diet i.e. fats and carbohydrates (Ambrose & Norr, 1993; Lee-Thorp et al., 1989). Even when the proportions of carbohydrates, proteins and fats in the diet are altered the $\delta^{13}C$ of dental enamel carbonate seems to accurately reflect the composition of the whole diet (Ambrose &Norr, 1993), though there is systematic enrichment in ^{13}C (leading to higher $\delta^{13}C$) between the diet and enamel carbonate of 6-15‰. This has been shown using controlled diet studies conducted on rodents (Ambrose & Norr, 1993), ungulates (Balasse, 2002) and mammals (Passey et al., 2005), and relates to the fractionation of carbon due to metabolic processes. The exact magnitude of this enrichment appears to be dependent on the digestive physiology of the animal in question (Passey, 2005).

9.7 What information can carbon isotope ratios give the archaeologist?

The basic C_3 and C_4 fractionation differences in plants mean it is possible to separate individuals primarily using C_4 plants, such as maize and millet, from those subsisting on more common C_3 plants. For the most part though, carbon isotope ratios cannot be used toidentify specific food types used by the individual. Instead they give broad information on the food groups being consumed.

Carbon isotope analysis is also useful in conjunction with strontium isotope analysis, as strontium isotope ratios may indicate that individuals are migrants when in actuality they were merely using food sources from different geological areas. Having carbon isotope data from these individuals shows whether or not dietary differences may be causing 'false positives'. Typical carbon isotope ratio variation within food groups is shown on figure 9.2.

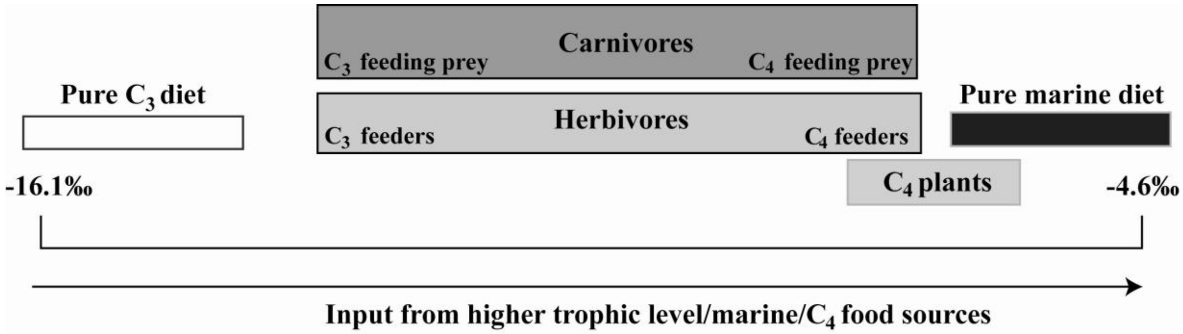


Figure 9.2: Expected $\delta^{13}C$ values in human dental enamel for different dietary inputs. After King (2006).

9.8 Expected Carbon Isotope Ratios in UMRV individuals

Work by King (2006; 2008) indicates that sites of the UMRV are likely to have had a C_3 plant and terrestrial protein dominated diet. In small-scale studies at Ban Lum Khao and Noen U-Loke carbon isotope ratios in dental enamel ranged between -9.5‰ and -14.6‰ (King, 2006; Bentley et al., 2009b; Cox et al., 2011).

Archaeozoological and archaeobotanical analysis at Ban Non Wat, Noen U-Loke and Ban Lum Khao indicates that rice agriculture was in place from the early Neolithic (Higham, 2003; Castillo, pers. comm). Archaeozoological analysis of middens at BNW shows a dominance of domesticated species of bovid and suid, though game species such as cervids were also present (Higham et al., 2007; Higham & Thosarat, 2005; Higham, 2009). Freshwater fish species common in stream, swamp and wet rice paddies such as Chanidae, Belontiidae and Clariidae were also common in midden deposits of all three sites.

There is, as yet, no evidence of C_4 crops being cultivated in the UMRV and the geographic location of the valley also make it highly unlikely that marine resources were in use. It is therefore unlikely that individuals native to the UMRV will have carbon isotope ratios falling higher -8‰ (PDB).

9.9 Oxygen Isotope Ratios

Oxygen isotope ratios are used as a proxy for the water source used by an individual, and climatic conditions at the time of enamel mineralisation. Similar to carbon isotopes, they are not reported simply as a ratio, but instead relative to a standard in parts per thousand (‰), this allows significance of differences in ratio to be more easily evaluated. Commonly used standards for oxygen isotope analysis include PDB and SMOW (standard mean ocean water). In this study SMOW is used, primarily to maintain consistency with already published archaeological studies. Calculation of $\delta^{18}O$ follows the same formula as calculation of $\delta^{13}C$ i.e.

$$\delta = \left[\frac{\left[\frac{^{18}O}{^{16}O}\right] sample}{\left[\frac{^{18}O}{^{16}O}\right] SMOW} - 1 \right] 1000$$

Oxygen isotopes are fractionated on the basis of evaporation/condensation events, with heavier ^{18}O preferentially ‘rained out’ after evaporation as it forms stronger bonds than ^{16}O (Araguas-Araguas et al., 1998). This means that oxygen isotope ratios vary geographically with water sources closer to the sea, and the equator generally containing more ^{18}O than those in inland areas. Oxygen isotopes values can therefore be used to clarify patterns in strontium isotope ratios, as they also contain a geographic signature.

In Thailand there is significant oxygen isotopic fractionation based on a ‘rainshadow’ effect which occurs in the Khorat Plateau (King, 2006). Here the Phetchabun, Dong Phrayayen and Dang Rek ranges cause precipitation (and depletion in ^{18}O) before rain reaches the Khorat Plateau. Microclimatic variation is evident in that the north and northeast margins of the area get the most rain and the western and central regions the least (King, 2006). Any rain which falls in the west and central regions is likely to be enriched in ^{16}O relative to the north and northeast.

Use of oxygen isotopes as an indicator of geographic origin is not as clear-cut as simply matching $\delta^{18}O$ in dental enamel to a water source. Humans and other animals rarely use a single water source, and their isotopic ratios will reflect this mixing. Studies in animal biology have indicated that oxygen isotope ratios in animal tissue and food products broadly speaking, do echo those found in their water sources (e.g. Manca, et al., 2001; Wassenaar and Hobson, 2001). It does appear, however, that oxygen undergoes further fractionations within the body due to factors such as metabolic rate, heat loss mechanisms, waste removal mechanisms and respiratory patterns. This results in different genera of animals, even within a single geographic area, often having a wide range of $\delta^{18}O$ (Kohn, et al., 1996).

Oxygen isotope ratios are not only dependent on geographic location; they also vary between years and seasonally, depending on the amount of rainfall occurring at any given time (Rozanski et al., 1992; Koch et al., 1989). Oxygen isotopes are, therefore, an important proxy for climate. Dansgaard (1964) has shown that there is a clear correlation between oxygen isotope ratio and climate change, with an inverse relationship between the amount of rainfall and $\delta^{18}O$ in the tropics. This means that in order to interpret oxygen isotope results obtained in this study a consideration of palaeoclimate/environment is required.

9.10 Palaeoclimate in Southeast Asia

In Southeast Asia paleoclimate is fundamentally linked to the strength of the Asian monsoon, which dictates rainfall levels and periods of drought (Cook et al., 2010; Clift & Plumb, 2008). Changes to monsoonal intensity have been hypothesised as reasons for changes seen in human society (e.g. Cook et al., 2010; Buckley et al., 2010), and it is this which makes the paleoclimate significant to any study of social complexity in the region.

Paleoclimate may be reconstructed using a number of proxies, chief among which are oxygen isotopes, sediment lithology and vegetation reconstruction. These have been employed in Southeast Asia in various studies (e.g. Maxwell, 2001; Wang et al., 2005; Dykoski et al., 2005), but there remains a paucity of data regarding the Holocene climate in Thailand (Wohlfarth et al., 2012). Fortunately for this study one of the few areas which has undergone extensive investigation is Lake (Nong) Han Kumphawapi (Penny et al., 1996; Kealhofer & Penny, 1998; Wohlfarth et al., 2012), situated just north of the Upper Mun River Valley, still within the Khorat Plateau (figure 9.3).

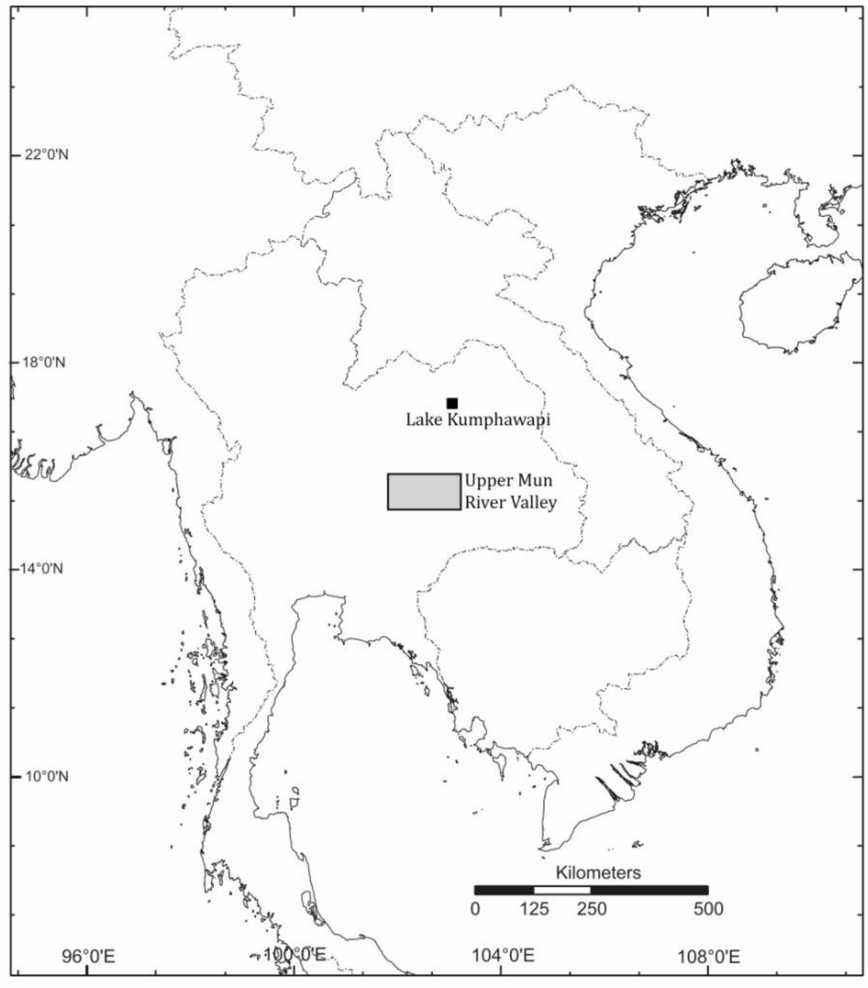


Figure 9.3: Giving the location of Lake Kumphawapi relative to the UMRV.

Study of the lake sediments using palynological, isotopic, and sedimentary analysis has built up a temporally resolved picture of the paleoclimate of Northeast Thailand over a period of about 10,000years. During the period of occupation of Ban Non Wat (3700BP – present) the lake's sediments show a series of hiatuses in deposition correlating with dry episodes between 2700-2500BP and 1900-1600BP (Wohlfarth et al., 2012). This compares well with the evidence for a decline in the Asian monsoon shown in stalactite isotope records (Wang et al., 2005) and the evidence for decreased water availability seen in the archaeological record around this period (Boyd, 2008), though it does contrast with the pattern of strengthening monsoon seen in the sediments of Lake Kara (Maxwell, 2001). An overview of the information gained from climatic proxies in Southeast Asia during the period of Ban Non Wat's occupation is given on figure 9.4.

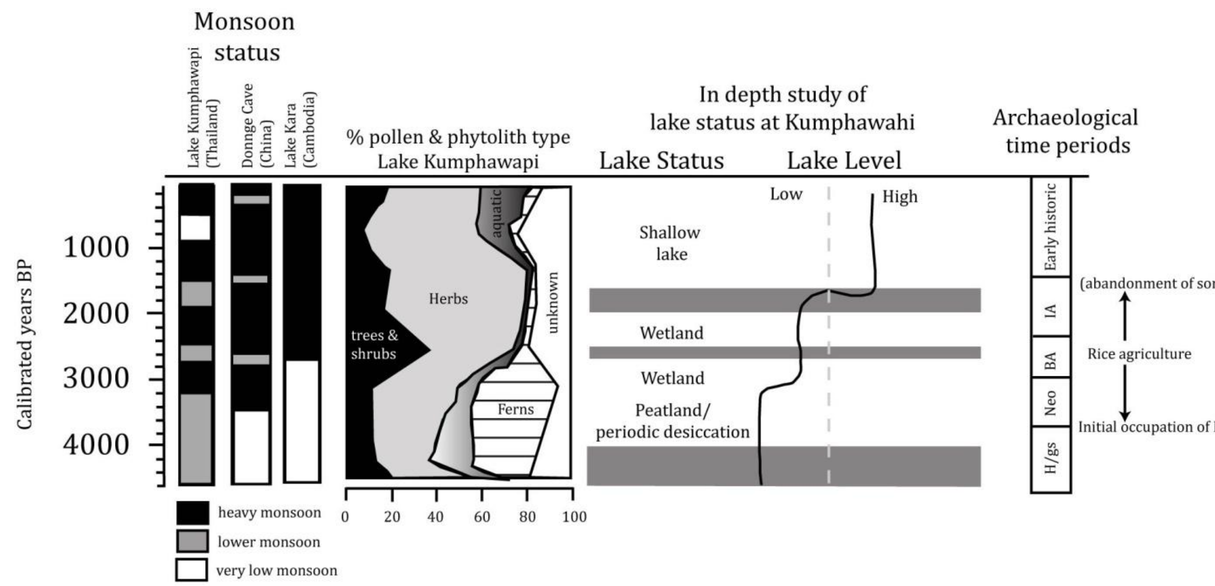


Figure 9.4: Information on monsoon strength from Wohlfarth et al. (2012), Wang et al. (2005) and Maxwell (2001), correlated with floral analysis from Lake Kumphawapi (Penny et al., 1996), inferences on lake level and therefore effective moisture levels (Wohlfarth et al. (2012) and archaeological occupation of the Upper Mun River Valley (Higham & Kijngam, 2011).

9.11 Expected Oxygen Isotope Ratios in the UMRV

The location of Lake Kumphawapi on the same plateau as the UMRV means it is the best proxy available for evaluating the climatic variation likely to have been occurring around Ban Non Wat during its occupation. It will also provide an important context within which oxygen isotope results may be evaluated. If the periods of hiatus at Lake Kumphawapi represent a large scale event then it might be expected that oxygen isotope results obtained will reflect this dryness, and some Iron Age individuals may have substantially higher $\delta^{18}O$ reflecting the lack of effective moisture present at their time of enamel mineralisation (c.f. Dansgaard, 1964).

Previous isotopic studies in Southeast Asia (e.g. Krigbaum, 2003; Bentley et al., 2005; Cox et al., 2011) have shown that it is difficult to predict the oxygen isotope composition of water in any given area, and it certainly does not appear easy to differentiate different geographic areas based on their $\delta^{18}O$. It was therefore expected that oxygen isotope ratios would be most useful in highlighting individuals with vastly different geographic origins, or as indicators of climatic change within this study.

9.11a Predicting $\delta^{18}O$ using the relationship between $\delta^{18}O$ in groundwater and $\delta^{18}O$ in dental enamel:

Many have explored the relationship between $\delta^{18}O$ in teeth and $\delta^{18}O$ in groundwater (Luz et al., 1985; Longinelli, 1984; Levinson et al., 1987; Daux et al., 2008). The primary aim of these studies has been to establish the $\delta^{18}O_p$ (dental phosphate) expected in specific geographic locations, thus allowing tracing of prehistoric mobility (e.g. Chenery et al., 2010; Leach et al., 2010; Pollard et al., 2011).

The process involved in this correlation is an inverse regression, where $\delta^{18}O_p$ is plotted against $\delta^{18}O_w$ to give a correlation coefficient, allowing the calculation of expected values in unknowns (Pollard et al., 2011). It has been recognised that the predicted value of $\delta^{18}O_p$ varies depending on which regression is used (Daux et al., 2008) but, in general, published errors on predicted values are given as <1‰, implying a high level of statistical power.

Daux et al. (2008) have explored this correlation between $\delta^{18}O_w$ and $\delta^{18}O_p$, and the effect of using different regressions to predict unknowns, to create an over-arching equation for calculation (equation 6 in Daux et al., 2008, given below).

$$\delta^{18}O_w = 1.54\ (\pm 0.09) \times \delta^{18}O_p - 33.72\ (\pm 1.51)$$

where the correlation coefficient is given as: $R^2 = 0.87$: $p[H_0:R^2 = 0] = 2 \times 10^{-19}$

This equation has been used frequently archaeologists seeking to use $\delta^{18}O_w$ to predict the $\delta^{18}O_p$ expected in 'local' individuals (e.g. Smits et al., 2010; Millard & Schroeder, 2010; Perry et al., 2009).

If this equation is applied to $\delta^{18}O_w$ data from modern Thailand (IAEA/WMO, 2006), where precipitation has an annual mean $\delta^{18}O$ of -6.59‰, it can be rearranged to give an estimate of the expected $\delta^{18}O_p$ in the teeth of BNW. In this case using eq. 6 of Daux et al. (2008) gives expected values of 17.6‰ (±1.89).

This can be converted to the expected value of $\delta^{18}O_c$ (dental enamel carbonate), since in this study isotopes were measured in carbonate not phosphate, using Chenery's (2012) equation (below).

$$\delta^{18}O_p = 1.0322\ (\pm 0.008) \times \delta^{18}O_c - 9.6849\ (\pm 0.187)$$

This gives an expected $\delta^{18}O_c$ of 26.5‰ (±1.92). Based on climatic data discussed in section 9.10 actual $\delta^{18}O_c$ in BNW dentition may be expected to be higher than this, reflecting drier conditions during prehistory.

9.11b Errors:

If the regression equations detailed in section 9.11a are to be used with any statistical power the error on results must be smaller than any possible regional/temporal variation (Pollard et al., 2011). In Thailand, for instance, modern oxygen isotope data indicates there is variation of up to 3‰ inter-regionally, and monthly variation of up to 5‰ due to the effect of the monsoon (IAEA/WMO, 2006). If errors on predicted $\delta^{18}O_p$ are larger than this, then geographic resolution is essentially impossible.

While errors reported on predicted $\delta^{18}O_p$ from original studies are generally lower than 1‰, Pollard et al (2011) have shown that the standard deviation on all commonly used regression equations results in error greater than 1‰ and up to 5.5‰, depending on the equation used and number of repeat measurements taken of the known variable.

As a result of this it seems more prudent to base expected $\delta^{18}O_c$ on those previously obtained in studies within the study region (as with Müldner, 2010). In this case previous isotopic studies conducted in the UMRV have shown local $\delta^{18}O$ ranges between 25.7‰ and 28.5‰ at Noen U-Loke (Cox et al., 2011) and and 24.2‰ and 27.5‰ at Ban Lum Khao (Bentley et al., 2009b). Ban Non Wat lies closer to Noen U-Loke than Ban Lum Khao, and on the same system of paleochannels (Boyd et al., 1999). It is therefore likely that oxygen isotope ratios at Ban Non Wat will lie closer to those found at Noen U-Loke.

9.12 Method of Analysis- Carbon and Oxygen Isotopes

Dental enamel was crushed to a homogenous powder using an agate pestle and mortar. 5.5mg enamel was then weighed out using a microbalance, placed into glass vials and sealed. Vials were flushed with helium gas for 4-6 hours to remove atmosphere before analysis. Pressure in the vials was relieved through puncturing with a sterile needle, then 30 drops 6MolL^{-1} phosphoric acid (H_3PO_4) were manually injected into each vial. The sample was allowed to dissolve in phosphoric acid for two hours prior to analysis. Carbon dioxide produced during this reaction was then separated using a GasBench II chromatograph. Isotopic ratios were measured using a Thermo Electron MAT253 mass spectrometer. During mass spectrometry, each vial was sampled automatically using a mechanised needle. Isotopic results reported in this thesis represent single measurements of each sample.

Isotope ratios were normalised to standards NBS 19 and LSVEC, and were standardised using repeated measurements of internal standard DCS01. Standard deviation of DCS01 measurements during the period of analysis was 0.05‰ for $\delta^{13}C$ and 0.04‰ for $\delta^{18}O$ (2sd.). Accuracy of sample measurements was established using repeat measurements of selected samples (B144 and B263), giving analytical error as 0.18‰ (1sd).

9.13 Establishing a protocol for carbon and oxygen isotope analysis using dental enamel

Mass spectrometry at the NCIET (Northern Centre for Isotopic and Elemental Tracing) is generally conducted upon carbonate minerals, not human tissue. An experiment to work out how much sample and acid were required to give measurable results, was needed prior to embarking on this study, to ensure yield was maximized and results were repeatable.

9.13a Materials

Only one tooth sample was used in this experiment; that of BNW 3:1, a 3rd mandibular molar of domestic pig (*Sus scrofa)*. This sample was chosen because it is a large, complete molar, giving a good amount of material, and ensuring that a human tooth was not destroyed purely to establish a protocol.

9.13b Method

12 samples from this molar were prepared; four samples of 5.5mg, four of 6.5mg and four of 8mg weight. In each of these weight categories two samples had 10 drops of phosphoric acid (H_3PO_4) added, one 20 drops, and one 30 drops. These samples were then analysed through mass spectrometry at the NCIET according to the method laid out above.

9.13c Results

The $\delta^{13}C$ and $\delta^{18}O$ values, normalised to NBS-19 and LSVEC international standards, are presented in figure 9.5.

Oxygen isotope results were most reproducible for those samples which had 30 drops of acid added to them. Carbon isotope values were reproducible in samples with either 20 or 30 drops of acid added. During analysis it was also noted that the beam size was most stable with the standards corresponding with the samples of 5.5mg weight. The amounts of reactants used during this study were therefore set as: 5.5mg sample, ground to a homogeneous powder and 30 drops phosphoric acid.

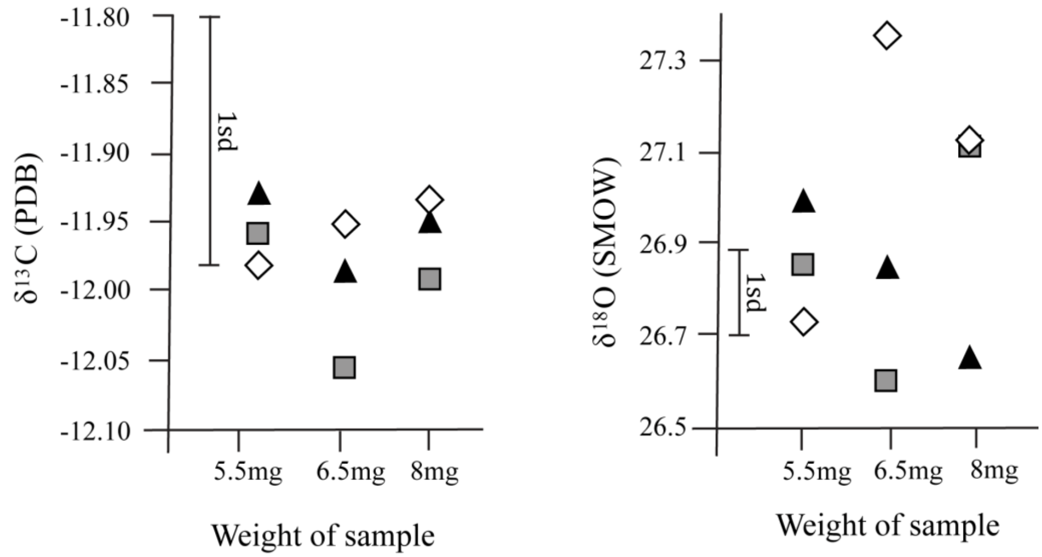


Figure 9.5: Results of reagent quantity testing. White diamonds = 10 drops acid, grey squares = 20 drops, black triangles = 30 drops. Carbon isotope results (left) for test show good agreement regardless of the number of drops of acid added, and most similarity at 5.5mg. Oxygen isotope results (right) show most agreement when 30 drops of acid is added, and most similarity at 5.5mg.

10. Statistical Testing

"To understand God's thoughts one must study statistics…the measure of his purpose"

Florence Nightingale (cit. in Everitt, 1999)

The generation of large results datasets means that statistical testing is necessary in order to establish whether or not patterns are significant. Statistical testing is used in this study to analyse homogeneity of variance and differences in means, and establish whether or not outliers are truly significant. The main statistical tests used are set-out and explained in this section.

10.1 Statistical Significance

In statistical testing the value of p is the probability of the null hypothesis being correct. The null hypothesis is rejected if p is less than the significance level (α). α is defined by the researcher, often as 0.1 or 0.05. In this study α is set as 0.05. When p is less than 0.05 the null hypothesis is rejected and the result is statistically significant.

10.2 Student's T-test

T-tests are used to compare the means of two samples to establish whether or not they differ in a statistically significant way. The null hypothesis in this test is that the means of the two groups are equal, any significant p value therefore indicates that the means of the groups are significantly different. In this study 2-tailed *t*-testing is used to establish whether or not there are significant differences in isotopic ratios between males and females, or between sites. 2-tailed *t*-tests assume that that the samples are independent of one another and that the groups are normally distributed, though the large sample sizes dealt with in this study means that this assumption can be relaxed (Shennan, 1997). Student's *t* is calculated as a ratio of the difference between the means of the groups, and the variance around those means (Zelditch et al., 2004).

10.3 Levene's test for equality of variance

Many parametric tests assume that the groups being compared have equality of variance, and if this assumption is not met significance values will be affected. Levene's test is used to evaluate whether this is the case. In this study the equality or lack of equality of variance between groups such as males and females is also interesting in and of itself.

10.4 One-way ANOVA

Analysis of variance (ANOVA) tests whether the means of multiple groups differ significantly. In one-way ANOVA the variance in the sample is portioned into two linearly independent components; the difference among groups, and the variance within groups. If the difference among groups is significantly larger than the variance within groups then the null hypothesis (of homogeneity of means) is rejected (Legendre & Legendre, 1998). In this study ANOVA is primarily used to assess whether isotopic differences between mortuary phases are significant.

10.5 MANOVA

Multivariate analysis of Variance (MANOVA), is similar to ANOVA testing, but allows analysis of data that involves more than one dependent variable at any one time. It uses variance-covariance between variables to test whether or not differences between means are significant. In this study MANOVA has been used to look at differences in isotopic mean between male and females, and mortuary phases concurrently (i.e. sex and mortuary phase are the two dependant variables analysed).

11. Dental Non-Metric Trait Recording

"These ridges and depressions in some teeth look rather insignificant, in others confusing…[a closer study] soon shows, however, that they are not mere fortuitous formations"

-Hrdlicka, 1921

11.1 Recording non-metric traits

Non-metric traits in the human skeleton are those which cannot be measured, instead they are features which are recorded as present/absent. Because these traits cannot be measured there is a certain degree of subjectivity to their recording, and inter-observer error can be a major problem. The assumption in recording non-metric traits is that they are correlated with genetic relatedness, and much research has gone into proving whether or not this is the case (Carson, 2006, Cheverud and Buikstra, 1981).

11.1a The heredity of dental non-metric traits

Most lines of evidence indicate that genes are a major controlling factor in crown and root trait development (Scott & Turner, 2000). The most in depth study of correlation between genetic links and dental traits is that of Berry (1978). This study used nonmetric traits related to the crown morphology of dentition in living family groups to explore the heritability between these features. It found that most commonly studied nonmetric traits (e.g. shovelling, Carabelli's trait, sagittal furrowing on PM_1, extra-lingual cusps) are significantly correlated to genetic relatedness ($p=<0.01$ in most cases). McKusick (1990) lists Carabelli's trait and shovelled incisors as having presumed simple modes of genetic inheritance, though Scott (1973) suggests that high frequency traits such as Carabelli's merely simulate a pattern of dominant inheritance.

In actuality the manner of inheritance of non-metric traits is stillnot well understood. It is certainly not simply a matter of dominant/recessive gene inheritance, and is likely to be complex and multifactorial (Berry, 1978). Authors such as Scott (1973) and Grüneberg (1963) suggest non-metric trait expression is quasicontinuous, allowing variable expression of the trait, not simply presence/absence.

These studies indicate that there is at least some level of heredity behind dental non-metric traits, and many studies have used the frequency of dental non-metric trait occurrence as a proxy for population affinity. These are detailed in section 2.5, their success indicates the usefulness of these traits in addressing questions of migration and population history.

There is, however, some doubt over the credibility of cranial non-metric traits as a proxy for genetic relatedness (Carson, 2006), therefore this study will be using only *dental* non-metric features.

11.1b Dental non-metric traits recorded in this study

The traits recorded in this study were chosen based on previous research into non-metric trait frequencies in Southeast Asia (e.g. Hanihara, 1968; Matsumura & Hudson, 2005), and are detailed in full in table 11.1.

Dental Non-Metric Trait	Description
Shovelling (on UI_1 and UI_2)	Marginal ridges become especially prominent, enclosing a deep fossa on the lingual surface.
Carabelli's cusp (UM_1)	Presence of an extra cusp arising from the base of the mesiolingual cusp in molars. Perhaps present as a cusp rivalling main cusps in size, or as a small ridge, pit or furrow.
Sixth/Seventh cusp (LM_1, LM_2)	Presence of a sixth/seventh cusp on the lower molars, usually located on the distal aspect of the occlusal surface. In most cases the $6^{th}/7^{th}$ cusps are only about a quarter of the size of the other cusps.
Deflecting Wrinkle (LM_1)	Wrinkle in the ridge of the metaconid curving distalward at the central part of the occlusal surface.
Hypocone (UM_2)	Presence of pronounced cusp on disto-lingual occlusal surface of the molar. Most humans have this cusp on UM_1, but its expression is variable in UM_2

Metacone (UM_2)	
Metaconule (UM_2)	Occlusal tubercle on the distal marginal ridge of upper molars. Between the Metacone and hypocone.
Peg-shaped teeth (second incisors)	Distal lobe of the incisors is reduced, giving a peg shape
Supernumary Teeth	Additional teeth, usually found lingual to the normal tooth row.
Enamel Extensions	Enamel present as a line or lobe extending below the line of the cementum, usually directed apically towards the bifurcation of the roots. Also includes enamel pearls, small spherical masses of enamel, unconnected with the crown, usually located at the point of root bifurcation.

Table 11.1: Giving anatomical description of the dental non-metric traits recorded in this study. Definitions after Hillson (1996).

11.1c Scoring dental non-metric traits

Dental non-metric traits may be recorded as present/absent or graded according to their severity. In this study the Arizona State University grading systems were used wherever applicable (Turner et al., 1991; Hillson, 1996). Traits and their scoring systems are given in table 2.

Trait	**Scoring System**	**Description**
Shovelling	Numerical score with severity 0-5	According to the ASU dental anthropology standards. 0 = 5=
Carabelli’s cusp	0-7	0 = no cusp 1 = very slight bulge on mesiolingual aspect of the molar. 7 = pronounced extra cusp on mesiolingual aspect
Sixth/seventh cusp	Presence/absence	
Deflecting wrinkle	0-5	0 = straight ridge. 2/3 = Deflecting wrinkle, difference between grades is based on how the end of the ridge contacts the ectoconoid.
Hypocone	0-5	0 = Absence to 5 = pronounced distolingual cusp.
Metacone	0-5	
Metaconule	0-5	
Peg shaped teeth	Presence/absence	

Supernumary Teeth	Presence/absence	
Enamel Extension	Presence/absence	

Table 11.2: Scoring systems used in recording of dental non-metric traits in this study.

12. Geometric Morphometrics

"Procrustes lived beside the road and had two beds in his house, one small the other large. Offering a nights lodging to travelers he would lay the short men on the large bed and rack them out to fit it; but the tall men on the short bed, sawing off as much of their legs as projected beyond it"

- *Graves (1996: 306)*

12.1 Introduction

Geometric morphometric methods are increasingly being applied to archaeological questions in order to better understand the past. In the most simplistic terms geometric morphometric research involves the measurement of shape using Cartesian landmark co-ordinates, and the statistical analysis of those shape co-ordinates. It provides an empirical method for assessing similarities and differences in form between samples. This makes it ideal for the study of skeletal metric traits, as it reduces subjectivity and inter-observer error which are often inherent in bioarchaeology. In this study, geometric morphometric analysis has been used to explore the shape relationships between individuals identified as 'migrants' through isotopic analysis, and those who are local. The potential for using geometric morphometrics to identify short-distance migrants who are isotopically invisible has also been explored as part of this research.

12.2 Geometric morphometric techniques vs. traditional craniometric techniques

Craniometric techniques became popular in the late 19th – early 20th century as a way of empirically separating races (e.g. de Lapouge, 1899) or supporting evolutionary theory (e.g. Darwin, 1859). They have been since been applied, with less of a Eurocentric slant, to study genetic relationships or differences within, and between, populations (Howell, 1973; Pietrusewsky, 2006; Hanihara et al., 2008; and section 2.7 for further detail).

Modern craniometric studies involve the multivariate analysis of collections of distance measurements. They are, however, fettered by the fact that they cannot take into account spatial relationships between variables. In traditional craniometric analysis all morphological variation in the sample must be imagined as occurring along the measurements taken, and the geometry of the shape is reduced to a series of disconnected lines. Geometric morphometric techniques, on the other hand, look at how landmark positions change in relation to one another. They do not measure linear distances, but instead consider the shape as a whole. This allows better description of how and where shape change is occurring.

Traditional craniometrics are also limited by the fact that they cannot consider shape without also involving the *size* of the specimen. In many samples the highest proportion of variability is accounted for by size differences, as evidenced by multiple studies of cranial morphology using traditional craniometric techniques (Joliceur and Mosimann, 1969; Keita, 2004). The differences relating to *shape* can be eclipsed by this variation, and become more difficult to assess. In addition to this shape differences can also be related to changes in size (Bookstein, 1989) and disentangling the two components becomes important in order to understand overall variation. In geometric morphometrics simple algebraic manipulations can be used to partition the form of a specimen into size and shape components. From here shape variation can be considered alone, or with reference to size differences if this is an important aspect of the study.

Geometric morphometric analysis generally involves statistical manipulation of landmark data, meaning it can be presented graphically i.e. as images showing the changing shape of a set of samples, or principal components charts showing the spread of morphological variation. Data is therefore easy to visualize and understand. This contrasts with traditional craniometric methods which are generally restricted to reporting data in long and difficult to understand tables.

12.3 The application of geometric morphometric techniques to archaeological problems

Anthropology was one of the first disciplines to embrace geometric morphometric techniques and apply them to biological problems, and the techniques are increasingly being used archaeologically as well. The study of form, whether it be in terms of ceramic vessels, stone tools or biological materials is often essential to classification systems in archaeology (Lenardi & Merwin, 2010). Analytical tools which allow the statistical quantification of shape are therefore very useful, as they bypass subjective analysis and give statistical evidence upon which typologies can be based. In addition to this, geometric morphometric analysis fits well with the needs of the archaeologist, as it allows the study of both small-scale and large-scale variation. Morphometric techniques are also a non-destructive way of gleaning large quantities of information from specimens which are rare and cannot be subjected to other forms of analysis (Bookstein et al., 2004).

To date geometric morphometric analysis has been applied to archaeological problems including whether or not *Homo floresiensis* morphology is indicative of pathology (Baab & McKnulty, 2009), how domestication and dispersal processes occurred (Ottoni et al., 2012), to definition of artifact typologies (Lenardi & Merwin, 2010). It is used to define functional differences in artifact shape (e.g. Lipo et al., 2012), growth trajectories (Strand Viðarsdóttir et al., 2002; McKnulty et al., 2006) and biological shape changes associated with processes such as domestication or culturally-mediated cranial deformation (Cucchi et al., 2011; Perez, 2007). Most significantly for this study, geometric morphometrics is also widely used to evaluate population affinities and genetic relatedness (Ross et al., 2004; Martínez-Abadías et al., 2006; von Cramen Taubadel, 2009).These studies are detailed in section 2.7, and provide a useful background to this research. They have highlighted the links between population and craniofacial variation, and the uses of geometric morphometric techniques in establishing population history.

12.4 Geometric Morphometrics Theory

12.4a Landmarks:

Geometric morphometric techniques are based on recording the co-ordinates of anatomical landmarks and comparing differences in the positions of these landmarks. The landmarks gathered must be homologous points i.e. discrete anatomical loci which are recognisable in all specimens (Zelditch et al., 2004). They must be positioned so as to fully describe the morphology of the specimen, and must remain relatively constant in their relationship with other landmarks. The importance of landmark homology cannot be overstated, as the mathematical techniques used in geometric morphometrics examine deformation in one set of points relative to a corresponding set of points forming a different shape. This means that points must actually *correspond* or analysis is pointless.

The structure of the human cranium means that it is relatively easy to define points which can be found repeatedly and reliably by the researcher (e.g. the intersection of suture lines, foramina), though it is more difficult on other bones which are not so structurally complex. In many cases a landmark may be necessary to fully define the geometry of the bone, but this point may not always be in the same place (Zelditch et al., 2004). For instance the most inferior point on the mastoid of the skull may change position according to sex, pathology or genetic controls on whether the mastoid is inferior or anterior pointing. These landmarks are less ideal for geometric morphometric analysis but out of necessity they are often used. Landmarks are often defined based on Bookstein's typology of landmarks (Bookstein, 1991), which gives an indication of how mathematically reliable they are. This typology is given in table 12.1, and the all landmarks used in this study are categorised accordingly (section 12.5).

Bookstein's Landmark Type	**Description**	**Example**
Type I	Optimal for geometric morphometric analysis. They are locally defined (can be located easily by particular structures without being reliant on the positions of landmarks further from them)	The intersection of the coronal and sagittal sutures on the skull (bregma)
Type II	More problematic and harder to define. Their position is not fully constrained by the position of local structures, but instead by local geometry. They are often at local maxima/minima of curvature.	The ends of bony processes e.g. the tip of the mastoid
Type III	Difficult to establish, not always homologous. This type of landmark is defined to a surface but not to a specific location. It is often an *extrema*, defined by its distance from other points	The most lateral point on the nasal cavity.

Table 12.1: Bookstein's (1991) typology of landmarks.

12.4b Comparing shape using geometric morphometrics

As mentioned in section 12.4, size and shape are usually intimately linked by biological processes, and so the study of shape alone can be problematic. Shape is defined as “all the geometrical information that remains when location, scale and rotational effects are filtered from an object” (Kendall, 1977), and in geometric morphometrics a shape is represented by a configuration of landmarks. In order to study shape according to Kendall’s definition each of the landmark configurations gathered during data acquisition must first be centred and scaled (to account for location and scale differences) and then rotated (to eliminate differences in orientation). This effectively superimposes each of the shapes to be analysed. There are several methods of superimposition but the most common of these is the Procrustes Generalised Least Squares (GLS) method – also known as General Procrustes Analysis (GPA).

12.4c General Procrustes Analysis (GPA):

Stepwise the Procrustes analysis has been presented by Rohlf & Slice (1990) as:

1) Centring each configuration of landmarks.
2) Scaling each configuration of landmarks.
3) Choosing one configuration as a reference then rotating all other to minimise the partial Procrustes distance between them (i.e. minimising the summed squared distances between homologous landmarks).

Note here that step 1 is done with reference to the centroid position. This is position of averaged co-ordinates of a landmark configuration. Step 2 is done with reference to centroid size, which is the square root of the summed squared distances of each landmark from the centroid (position) of the landmark configuration. Step 3 is repeated with reference to an average shape calculated after the first iteration of step 3. This is reiterated until the newest reference shape calculated after step 3 is performed is the same as the previous.

This process is illustrated using triangles as an example in figure 12.1.

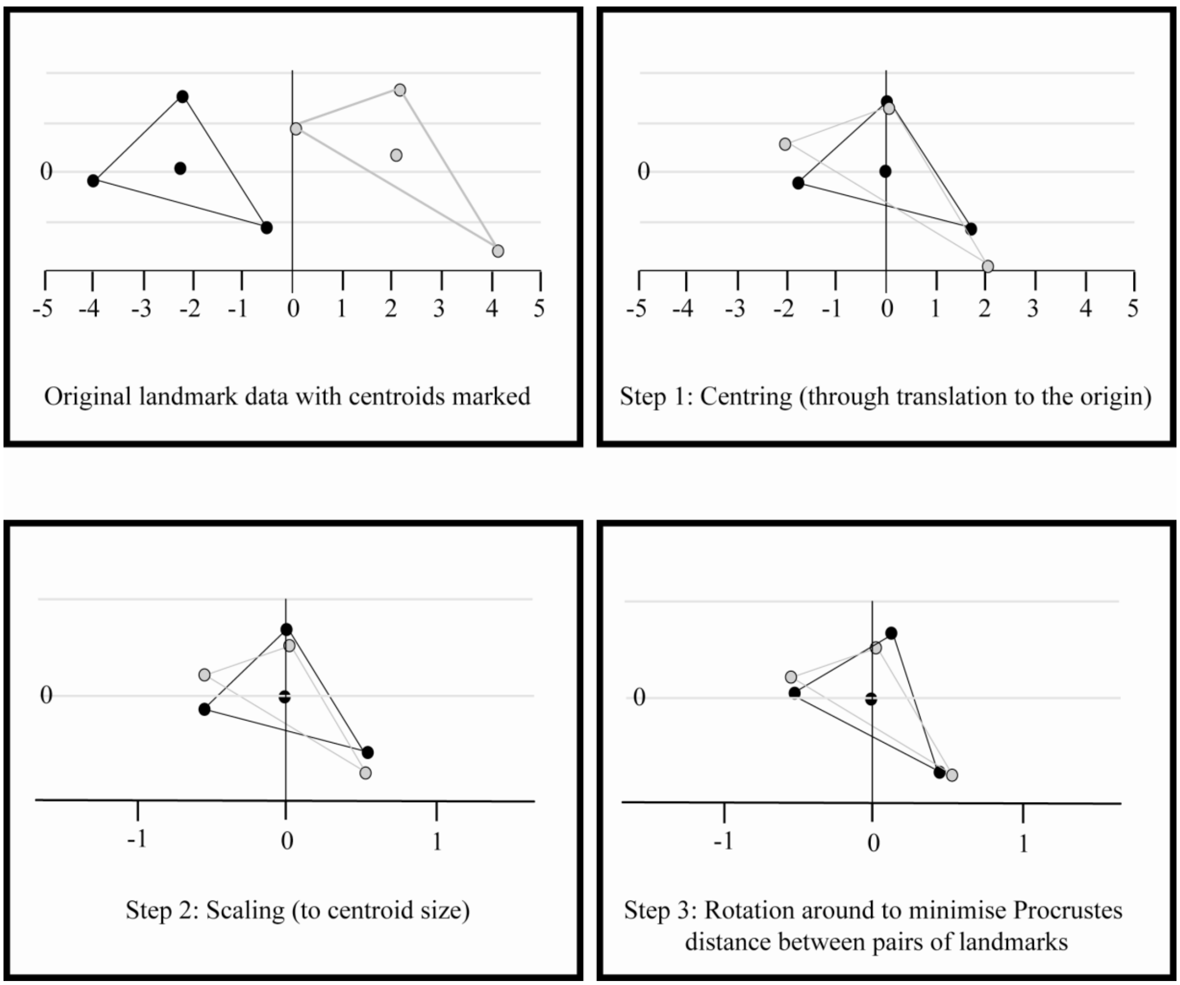


Figure 12.1: Showing visually the process of General Procrustes Analysis (after Baab, 2012)

12.4d Kendall's shape space, Slice's (hyper)hemisphere and tangent space:

Once a Generalized Procrustes Analysis has been executed, any configuration of landmarks can be represented as a single point within a highly dimensional shape space (Baab et al., 2012). The dimensions needed of the shape space are given by the general formula:

$$pk-k-k(k-1)/2-1$$

where p= the number of landmarks and k= the number of dimensions of the landmark data (Slice, 2005).

With each landmark configuration (shape) represented by a point in this shape space the further apart the points representing them, the more they differ morphologically.

The best-known shape space is Kendall's shape space (Kendall, 1984; 1989), where if configurations of three landmarks are visualized on the surface of a sphere. Slice (2001), however, has shown that once GPA has been applied this results in all shapes lying on a (hyper)hemisphere. It has the same unit radius and dimensionality of Kendall's shape space, but is not a full sphere.

Both Kendall's shape space and GPA space are non-Euclidean, which means that standard parametric statistical methods cannot be applied to data within them. In order to apply statistical tests datapoints must be projected into a Euclidean space known as tangent space, so named because it is constructed tangentially to GPA space at the point of the mean shape (Baab et al., 2012) (figure 11.2). The distances in tangent space approximate distances in

Kendall’s shape space as long as the variation within the sample is relatively small, large amounts of variation cause compression of the shape distribution when projected into tangent space (Rohlf, 1999). In this study, however, only intra-species variation is examined and so variation is unlikely to be large.

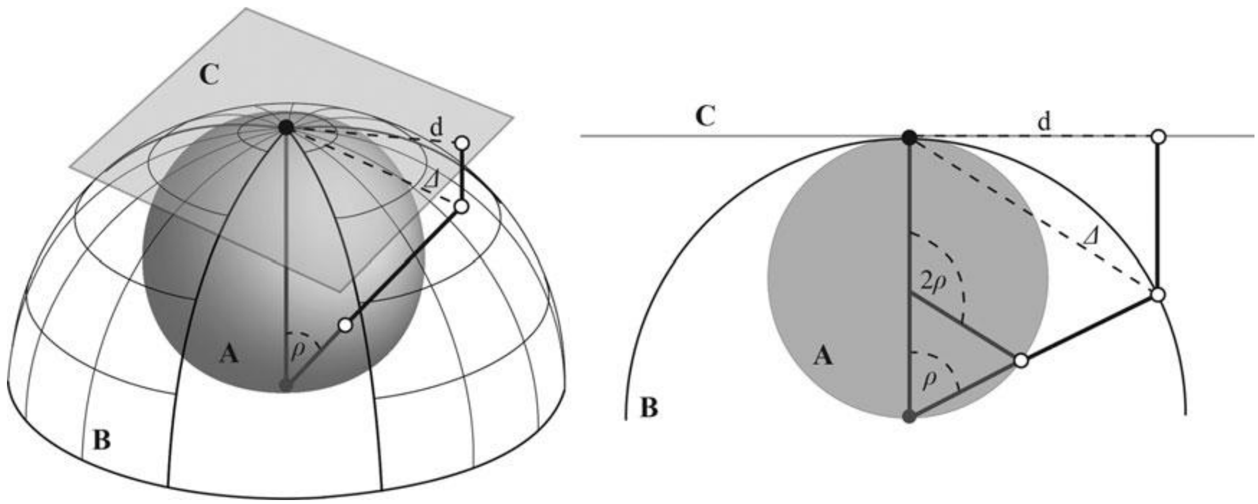


Figure 12.2: The relationships among shapes of three landmarks in (A) Kendall’s shape space, (B) GPA space (‘‘Slice’s shape space’’), and (C) tangent space (from Baab et al., 2012).

Most shape analyses occur in Slice’s GPA space, where distances between the samples are technically no longer ‘Procrustes distances’, though the term is still applied here and realistically there is rarely a large difference between Procrustes distances in GPA space, and those in Kendall’s shape space as long as distances between specimens are small (Baab et al., 2012).

12.4e Principal Component Analysis (PCA):

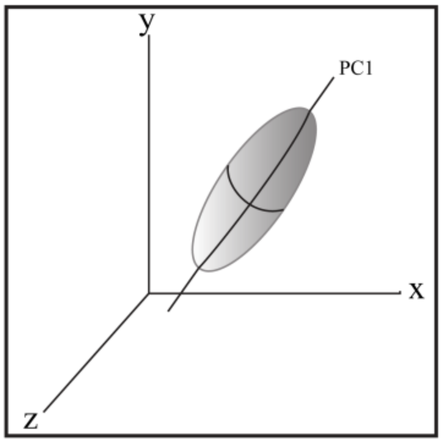
Biological patterns of variation are often complex and difficult to describe, in part because most biological structures function as an integrated whole and therefore shapes within them co-vary according to mechanical constraints. Principal components analysis is used to simplify the description of variation and make results easier to interpret. Put simplistically, principal components analysis replaces the original variables with new ones (principal components) which are linear combinations of the original variables and are independent of one another. This means that instead of having to consider the covariance of structures, and visualize multiple, small-scale variations within the original dataset, most of the variation within the sample can be explained using just a few principal components.

In geometric morphometrics principal components analysis is conducted on the sample covariance matrix based on Procrustes tangent space co-ordinates (Dryden & Mardia, 1998). When principal components analysis is carried out on data in the tangent space the variability is reduced into orthogonal components. Each principal component then successively explains the highest variability in the data (Dryden & Mardia, 1998). If, for example, sets of two dimensional landmark co-ordinates are analysed under PCA the stepwise procedure for analysis is as follows:

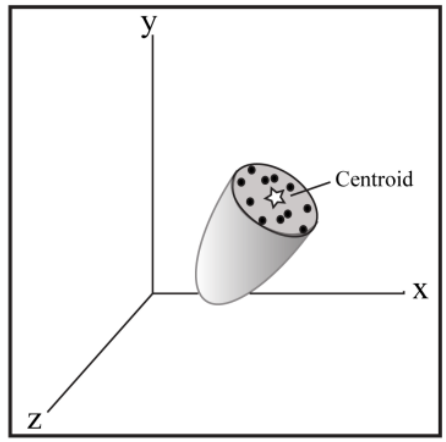
1) The mean value of each dimension is subtracted from each value i.e. x_1-$\bar{x}$, ,
2) A covariance matrix for this new data is constructed.
3) Eigenvectors and eigenvalues are calculated from the covariance matrix.

These eigenvectors are then scaled before computing the principal components, which give the co-ordinates on the axes (Legendre & Legendre, 1998).

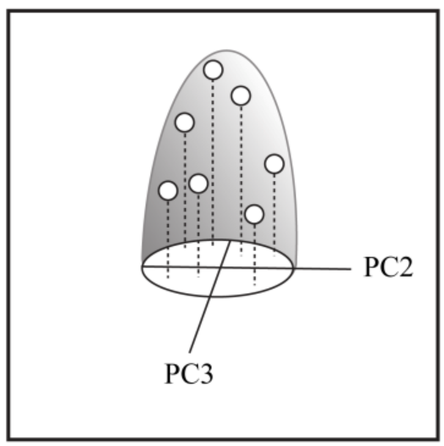
This process can be visualized as in figure 12.3.



All specimens are imagined as falling within a three dimensional ellipse. The longest axis of this is PC1, the line down which most variation occurs.



The ellipse is then bisected perpendicular to PC1, and through the centroid (mean shape)



The half ellipse is rotated, so the cross section is horizontal. The positions of the samples within the half ellipse are projected into this plane to give PC2 vs PC3

Figure 12.3: Visualisation showing the description of variation within a sample using principal components analysis (after Zelditch et al., 2004).

In many datasets only a few principal components will be required to explain the majority of shape variation seen. In structures such as the human cranium it is likely that some principal components will correspond to known types of variation e.g. the differences relating to sexual dimorphism or allometry.

In this study GPA and PCA were both computed using Morphologika (© O'Higgins, 2007) or EVAN (© Evan Society, 2012).

12.4f Canonical Variates Analysis (CVA)

The basic purpose of CVA in geometric morphometrics is to examine differences in shape between groups. CVA is very like PCA in that it constructs a new co-ordinate system from the procrustes data it analyses, in this case canonical variates, as opposed to principal components. Canonical variates are linear combination of the original variables and are orthogonal to one another.

Because CVA is used to look at differences between groups not differences between individuals it could be considered analogous to conducting PCA on group means. It does, however use the within-group variation in any sample to scale the axes of the plots produced. This means that groups will almost always appear spatially separated on a CV plot, but distances in CV space are not equivalent to distances in the original co-ordinate system, and results can be counterintuitive. In fact CVA is objected to by many morphometricians because its system of ordination does not preserve the Procrustes geometry (Mitteroecker & Bookstein, 2011), and because, when discriminant functions are calculated from CVA scores they cannot be related to biological factors (Bookstein, 1991).

In this study CVA is used to aid understanding, and visualize ways in which the groups within the sample are most similar or different, but it is acknowledged that it provides little information on statistical significance. Canonical variates analysis in this study was conducted in morphoJ (©Klingenberg, 2011).

12.4g Cross-validated discriminant function analysis (DFA)

Discriminant function analysis (DFA) is a tool used to predict group membership from a number of predictor variables. It is used in biology to predict taxonomic affiliation, dietary preference, sex and body size (Kovarovic et al., 2012).

In this study *cross-validated* discriminant function analysis is used to ensure group discriminations are meaningful. It has been shown by DeGusta & Vrba (2003) that under non-cross validated discriminant function analysis even a meaningless sample will be identified correctly to groups better than chance would suggest due to over-fitting of the data.

In order to ensure that discriminant function analysis is appropriate we have tested homogeneity of the covariances matrices using Box's M test for homogeneity of variance (cf. Kovarovic et al., 2011). Cross validation was applied using the 'leave one out' method in R (cf. Sickle et al., 2005; Ihaka & Gentleman, 1996).

It is acknowledged that unequal group sizes can affect the classification rate in discriminant function analyses (Evin et al., 2012), and so all CV DFAs were executed using the entire sample, and then using equal groups (i.e. only including a random sample of individuals from the larger groups to make them equal to the smaller). Randomisation tests (in which individuals were randomly assigned to groups) were also executed to understand what a 'chance' percentage classification was in any given sample (c.f. Evin et al., 2012).

12.4h Removal of sexual dimorphism from the sample

The human cranium is strongly affected by sexual dimorphism, so much so that cranial traits can be used to determine the sex of individuals after death (Buikstra & Ubelaker, 1994). Shape variation associated with sexual dimorphism is not of interest in this study, in fact it is likely to obscure the shape variation relating to population affinity and it is preferable to remove the effects of sexual dimorphism before statistical analysis is conducted. This was achieved using EVAN software using the process given below:

1) All data was procrustes fitted to remove scalar, translationaland rotational effects.
2) The sample was split into males and females using osteological data on each of the individuals in the analysis.
3) The mean landmark configuration for each sex was subtracted from each individual within the group. This standardised each sample to the mean for its sex.
4) The overall mean shape calculated during initial procrustes fitting was subtracted from each specimen, to remove the net effect of sexual dimorphism.
5) The sexes were then recombined and statistical analysis conducted as usual.

12.5 Landmark Sets

In the course of this study a suit of 42 landmarks was devised to describe cranial morphology. These were recorded using a Microscribe MLX (Immersion Corporation; San

Jose) digitising arm, with an accuracy of < 0.1270mm. Landmarks were taken unilaterally by placing the cranium on its right side and digitising the face, left side and basicranium. This meant all landmarks could be collected at the same time without introducing bias by moving the cranium. They are detailed in table 11.2 and figures 11.4, 11.5 and 11.6.

Number	**Landmark type**	**Description**
1	II	Midline at the most anterior point of the alveolar process of the maxilla (i.e. between the two anterior incisors)
2	II	Midpoint between the second incisor and canine on the alveolar process of the maxilla
3	II	Midpoint between the canine and 1st premolar on the alveolar process of the maxilla
4	II	Midpoint between the 2nd premolar and first molar on the alveolar process of the maxilla.
5	III	Most posterior point on the alveolar process of the maxilla
6	III	Most inferior point on the margin of the nasal aperture
7	III	Most lateral point on the margin of the nasal aperture.
8	III	Most inferior point of intersection of the nasal bone and the maxilla
9	I	Intersection of the two nasal bones and the frontal bone.
10	III	Most anterior midline point on the frontal bone.

11	I	Bregma (intersection of the coronal and sagittal sutures)
12	I	Lambda (intersection of the sagittal and lambdoidal suture)
13	I	Intersection of the lambdoidal, parietomastoid and occipitomastoid sutures.
14	I	Point where the temporal line crosses the coronal suture.
15	I	Point where the coronal suture intersects with the superior edge of the sphenoid.
16	I	Point of intersection between the zygomatic, sphenoid and frontal bones.
17	II	Most inferior point of intersection between the zygomatic and sphenoid.
18	I	Point where the frontozygomatic suture crosses the inner orbital rim.
19	I	Point where the frontozygomatic suture crosses the outer orbital rim.
20	II	Point where the temporal lie reaches its most anteromedial position on the frontal bone.
21	III	Most anterior point on the superciliary arch.
22	III	Most superior point of intersection between the maxilla and the nasal bone.
23	III	Most inferior and lateral position on the orbital rim.
24	I	Point where the zygomaxillary suture intersects with the orbital rim.

25	II	Most inferior point on the zygomaxillary suture
26	III	Point on the superior aspect of the orbital rim where a line drawn perpendicular from point 25 would intersect.
27	II	Most superior point on the infraorbital foramen
28	II	Most inferior point of intersection between the maxilla and the sphenoid.
29	III	Point of maximum lateral extent of the lateral surface of the zygomatic bone.
30	III	Point in the depth of the notch between the temporal and frontal processes on the zygomatic bone.
31	II	Most superior point on the temporozygomatic suture
32	II	Most inferior point on the temporozygomatic suture.
33	II	Most superior point on the margin of the external auditory meatus.
34	III	Point vertically above the centre of the external auditory meatus at the root of the zygomatic process of the temporal bone.
35	II	Most inferior point on the mastoid process
36	I	Point at which the frontomaxillary suture crosses the inner orbital rim.
37	I	Point of intersection between the occipital condyle and the jugular process.

38	I	Point of intersection between the occipital condyle and the lateral margin of the foramen magnum.
39	II	Midline point on the posterior margin of the foramen magnum
40	III	Point at which the superior nuchal lines merge in the external occipital protuberance.
41	II	Midline point on the anterior margin of the foramen magnum
42	II	Most anterior point on the interpalatal suture.

Table 12.2: Anatomical description of each of the landmarks recorded during this study.

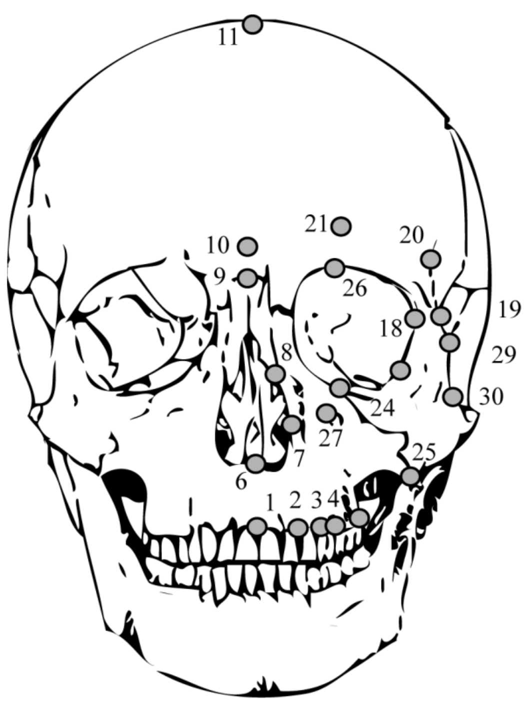


Figure 12.4: Facial landmarks collected during this study.

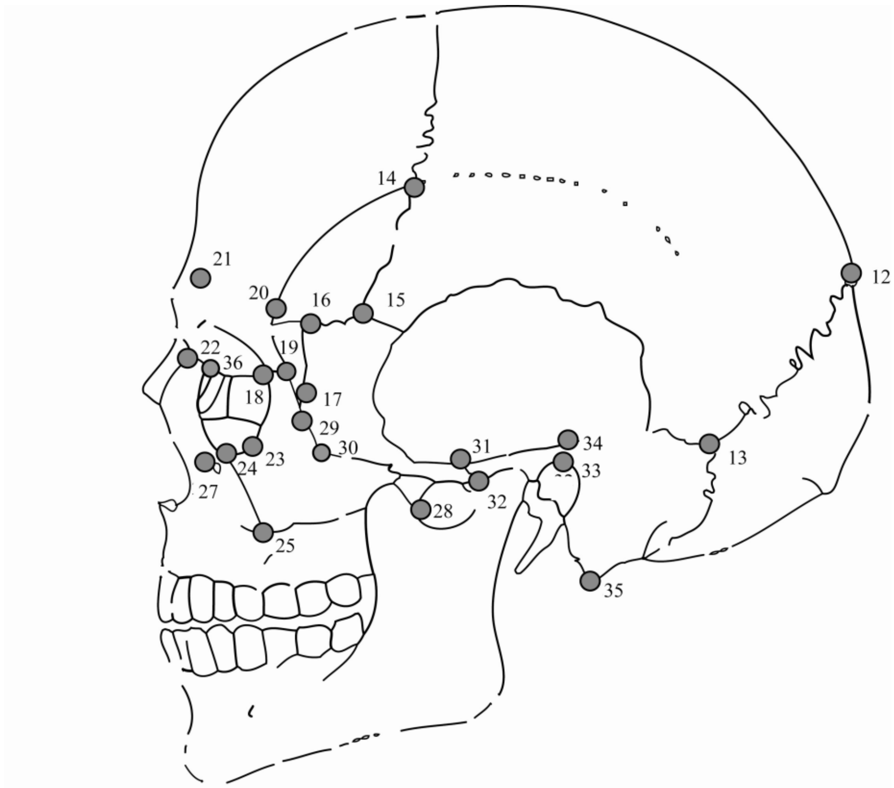


Figure 12.5: Lateral landmarks collected during this study.

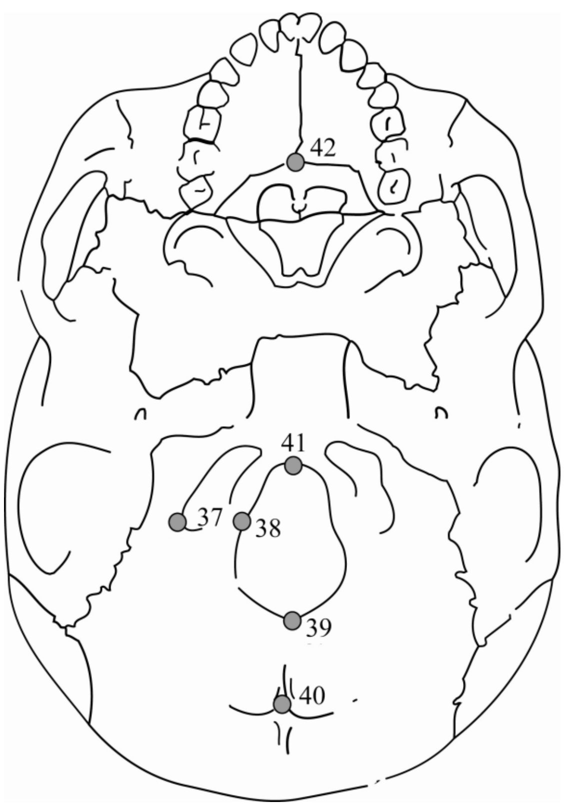


Figure 12.6: Basicranial landmarks collected during this study.

Not all of these landmarks were present on every cranium in the archaeological samplesanalysed. In particular the landmarks placed around the sphenoid and the basicranium were likely to be missing or obscured by concretion. To ensure maximum sample size all landmarks present were recorded and statistical analysis carried out on full sets of landmarks but also subsets of facial, vault and basicranial landmarks. The landmarks included in these subsets are given in table 12.3.

Subset of landmarks	**Landmark numbers included**
Facial	1-10, 18-26
Vault	10-16, 33-35
Basicranial	37-41

Table 12.3: Landmark subsets used during this study.

12.6 Estimating Intra-observer error

Digitisation was conducted by only one researcher in order to eliminate the possibility of inter-observer error. Intra-observer error was estimated by digitizing a single cranium 10 times on different days, and comparing results from this one specimen to those of an unrelated collection (O'Higgins & Jones, 1998). In this instance the cranium digitized is a randomly selected unknown from the reference collection at Durham University, the sample compared with is that of Fewston cemetery (a post-medieval English sample currently housed in the Fenwick Laboratory, Durham University). Results of principal components analysis of this error testing are plotted in figure 12.7. All repeats of the same cranium cluster away from the other samples, and tightly together at the positive end of

PC1, which represents 36% of total morphological variation in this sample. This indicates that the landmarks chosen are biologically significant, and that intra-observer error is small.

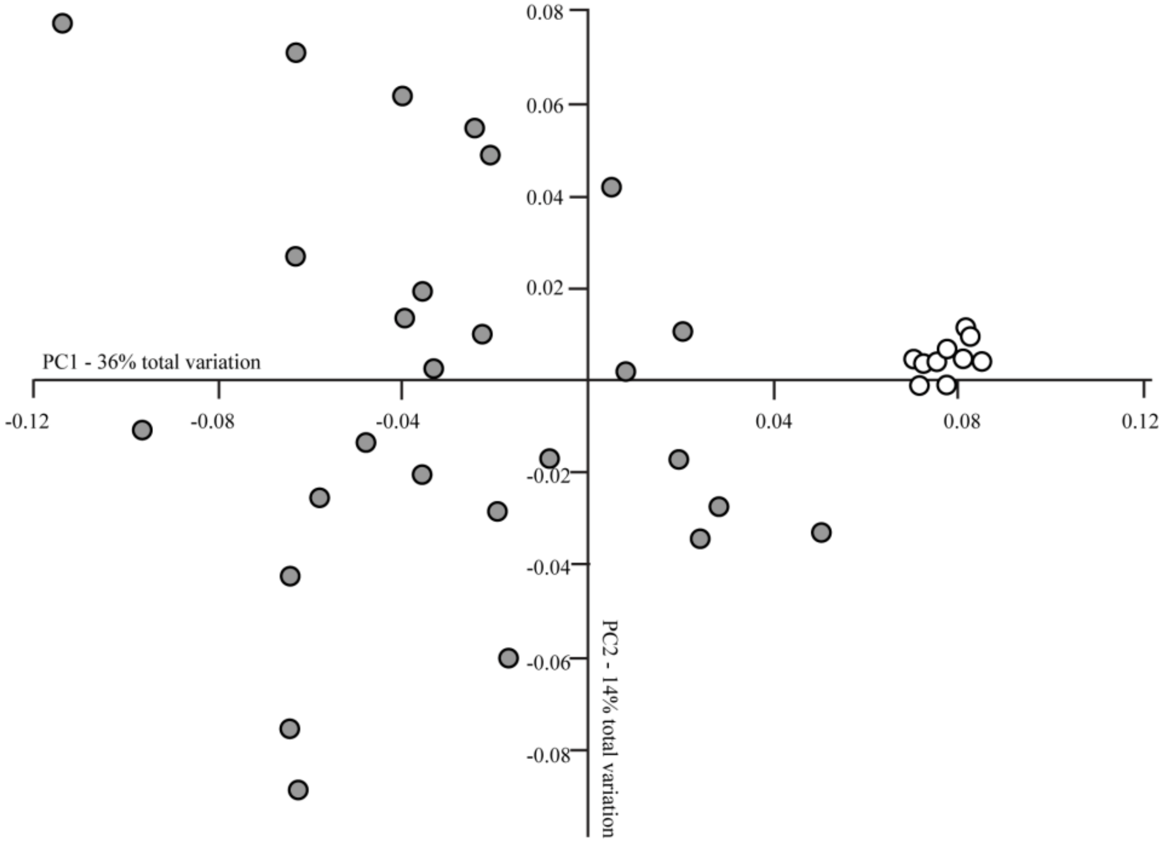


Figure 12.7: Principal components graph showing the results of error testing. Grey circle = reference sample (Fewston), white circles = repeated cranium.

13. Results

Here follows a series of papers submitted for publication (or prepared for submission) which detail the results of this study. Manuscripts one, two and three deal primarily with isotopic results, while four combines isotopic results with osteological data to identify migrant individuals and assess morphological affinities. Detailed below are details of the journals each manuscript has been submitted to, and the status of the articles at the time of thesis submission.

Social Organisation in the Prehistoric Mun River Valley: The story from the isotopes at Ban Non Wat.

Submitted to the Journal of Anthropological Archaeology, May 2012.Currently in review.

Mixed economies after the agricultural revolution in Southeast Asia?

Provisionally accepted for publication with Antiquity.

Moving peoples, changing diets: Isotopic differences highlight migration and subsistence changes in the Upper Mun River Valley, Thailand.

Accepted and published in the Journal of Archaeological Science.

Isotopes and Osteology: Using the multi-disciplinary approach to establish population affinity at Ban Non Wat, Thailand.

Prepared for submission to the American Journal of Physical Anthropology.

14. Manuscript One

Elsevier Editorial System(tm) for Journal of Anthropological Archaeology

Manuscript Draft

Manuscript Number: YJAAR-D-12-00049

Title: Social Organisation in the Prehistoric Mun River Valley: The story from the isotopes at Ban NonWat

Article Type: Research paper

Keywords: Thailand; strontium; carbon; hierarchy; heterarchy

Corresponding Author: Miss Charlotte King,

Corresponding Author's Institution: Durham University

First Author: Charlotte King

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Social Organisation in the Prehistoric Mun River Valley: The story from the isotopes at Ban Non Wat

Abstract

Ban Non Wat (ca. 2100BC – AD 400) is one of the largest prehistoric sites in the Upper Mun River Valley of Northeast Thailand. This area has long been of interest to archaeologists due to its excellent record of social growth from what is interpreted as an egalitarian society through to the emergence of complex hierarchies. There is, however, controversy over the form social evolution took in the area and whether or not migrant individuals had an impact on this growth. Here we add isotopic evidence to the investigation of social complexity. Our use of strontium, carbon and oxygen isotope ratios, measured in dental enamel from individuals sampled from Ban Non Wat cemetery, shows there is little evidence for long-distance migration into the population. The isotopic evidence can also be used to test hypotheses about social structure in the area, and from it we conclude that social evolution in the area may not have been as clear-cut as hierarchical approaches assume.

Introduction

In mainland Southeast Asia, most archaeological sites show a rise in social complexity including intensification and expansion of agriculture, inequality in burial wealth, and specialised pottery industries (e.g. O'Reilly, 2008) spanning from the Bronze Age (roughly 1000BC) though to the Iron Age (beginning around 400BC). Moated sites, associated with increased water control (Boyd, 2008) appear from the Iron age and state level of social organisation is present in many regions from 1000AD onwards (O'Reilly 2008; Higham 2002).

On the Khorat Plateau, our area of interest in NE Thailand, the introduction of farming practices occurs in the Neolithic, approximately 2nd millennium BC, and obvious status differentiation in burials is present by the Bronze Age, with the introduction of prestige items and evidence for craft specialisation (e.g. Higham & Kijngam, 2009). By the Iron Age, new metallurgical technologies allowed superior tools to be made, resulting in intensification of agriculture and the organisation of specialized labour. In Thailand, this culminated in the presence of the Angkorian Empire, in the late first millennium AD (Higham, 2002).

In the past there has been debate over whether or not complex society arose *in situ* in mainland Southeast Asia or was introduced by immigrants to the area (e.g. Coedes, 1968; Glover & Bellwood, 2005; Stark, 2006; Theunissen et al., 2000; Higham, 2003). Linguistic evidence and similarities in material culture suggest that the introduction of agriculture and bronze working in Southeast Asia is due to migration from southern China (e.g. Higham, 2003; Bellwood, 2001), but this does not answer questions about how immigration relates to the subsequent emergence of a social hierarchy.

This work focuses on the Upper Mun River Valley (UMRV), an archaeologically rich area of the Khorat Plateau. The sites of the UMRV include Noen U-Loke, Ban Lum Khao and Ban Non Wat, all of which are well known from the archaeological literature (e.g. Higham, 2002; Domett, 2004; Tayles et al., 2007; Higham & Kijngam, 2009). The study uses isotopic results to shed light on the processes of migration and social evolution in the UMRV's prehistory.

Strontium isotope analysis provides a geologically-related indicator of migration, and has been employed in previous studies at Ban Lum Khao (Bentley et al., 2009b) and Noen U-Loke (Cox et al., 2011). These studies have found little definitive evidence for long-distance immigration into the Upper Mun River Valley during its prehistoric phase of increasing social complexity. Only two individuals analysed from Ban Lum Khao (n=27), and none from Noen U-Loke (n=34) could be confidently identified as migrants (Bentley et al., 2009b; Cox et al., 2011). This contrasts with patterns seen at contemporaneous sites elsewhere in Thailand. At both Khok Phanom Di (2100-1500BC) on the coast, and Ban Chiang (2100BC-200AD) in the North of Thailand, probable migrant individuals of both sexes were identified in early phases of these sites, followed in subsequent phases by local signatures in females with male migration occurring (Bentley et al., 2005; 2007). In this study we aim to build on this work by analyzing individuals from Ban Non Wat, a cemetery large enough (over 600 individuals excavated) to represent a local population over two millennia (Higham, 2009).

Isotopic results will also be used to test hypotheses regarding the structure of society in the prehistoric Mun River Valley. There is currently debate over whether or not Southeast Asian society evolved along the trajectory describes by Service's (1962) model of primitive social organisation. Service's model is implicitly hierarchical, as it involves a rigid progression through band-tribe-chiefdom-state societies, with each phase being more 'advanced' than the previous. It is now recognised, however, that this model cannot be applied universally to archaeological contexts (Crumley, 1995). Quite apart from the inherent Eurocentrism of the typology we also have the problem that the archaeological data often simply do not fit comfortably within it. It is argued that Southeast Asia in general and Thailand in particular, is an area where this problem occurs (Bayard, 1992; White, 1995; White & Pigott, 1996; O'Reilly, 2001).

The evidence cited for the unsuitability of Service's model in Thailand includes the fact that the development of states occurs very late in the area's history (mid first millennium AD), well after the introduction of agriculture and metal working technology, these often being immediate precursors to the development of state society (e.g. Childe, 1950; Bellwood, 2005). When state formation does occur, much of its structure and characteristics are 'borrowed' from Indian and Chinese ideology. This has led authors such as Wheatley (1979) and White (1995) to hypothesise that there was no fixed model of hierarchy in place in Southeast Asia prior to state formation. They advocate the idea that societies in Southeast Asia existed as heterarchies. Heterarchical organisation is flexible, with individuals ranked in different ways in different contexts (Crumley, 1995). Change in status within a heterarchy can be based on personal achievement as well as wealth and kinship-based rank.

The archaeological evidence in the Mun River Valley has been interpreted as both hierarchical and heterarchical (see works by Higham and White for opposing perspectives). In all the known cemetery sites in the area there are clear differences in mortuary offerings which signify social differentiation. It is also clear that the level of differentiation increases over time. Some, such as Higham (2009) and Bacus (2006) have seen this as justification for applying the hierarchical approach, and use mortuary differences to trace society from an egalitarian base through to the emergence of a rigid social hierarchy.

Those who support the idea of heterarchy agree that the evidence for rank differences is strong but point to the continuum of grave wealth across age and sex boundaries at most sites as evidence that there are no demarcated boundaries in wealth between ranks, and therefore a more flexible ranking system is likely to have been in place (O'Reilly, 2001). Even Higham (1989) agrees the attainment of high status is likely to have been flexible during the Bronze Age, only becoming rigidly proscribed in the Iron Age. A lack of demarcated areas for the wealthy in many cemeteries is also interpreted as evidence for status being accorded based on personal achievement not family wealth/rank (O'Reilly, 2001; White, 1995). Higham (2011) contends that these arguments can only be made because of the limited excavated areas at the sites used as examples, and Ban Non Wat has been extensively excavated in order to overcome this limitation.

In short the field archaeological evidence is ambiguous, and patterns are interpreted differently depending on the archaeologist's perspective on social development. Here we add isotopic data tothe body of evidence available, in order to clarify the mode of social evolution in the UMRV. We hypothesise that if a rigid social hierarchy is in place this would lead to isotopic clustering as marriage exchanges become more rigidly proscribed and individuals from certain areas are routinely sought after as marriage partners for certain classes. This is an idealised scenario, based on marriage partners being sought from isotopically distinct areas; marriage partners from an isotopically similar area would not stand out. Clustering in carbon isotopes is likely to occur in a hierarchy as diet becomes more differentiated according to rank. There may also be a correlation between isotopic signature and mortuary wealth.

Under heterarchy we hypothesise less isotopic clustering, as marriage exchanges are more fluid and dietary differences not so marked. Although this scenario might also be expected in an egalitarian society, this possibility is ruled out by cemeteries in the Upper Mun River valley, which show definite evidence for social differentiation in their mortuary traditions after the early Neolithic phases. In contrast to hierarchy, heterarchy is less likely to involve a clear correlation between mortuary wealth and isotopic signature, as wealth is not ascribed from childhood. Figure 1 represents these hypothetical scenarios.

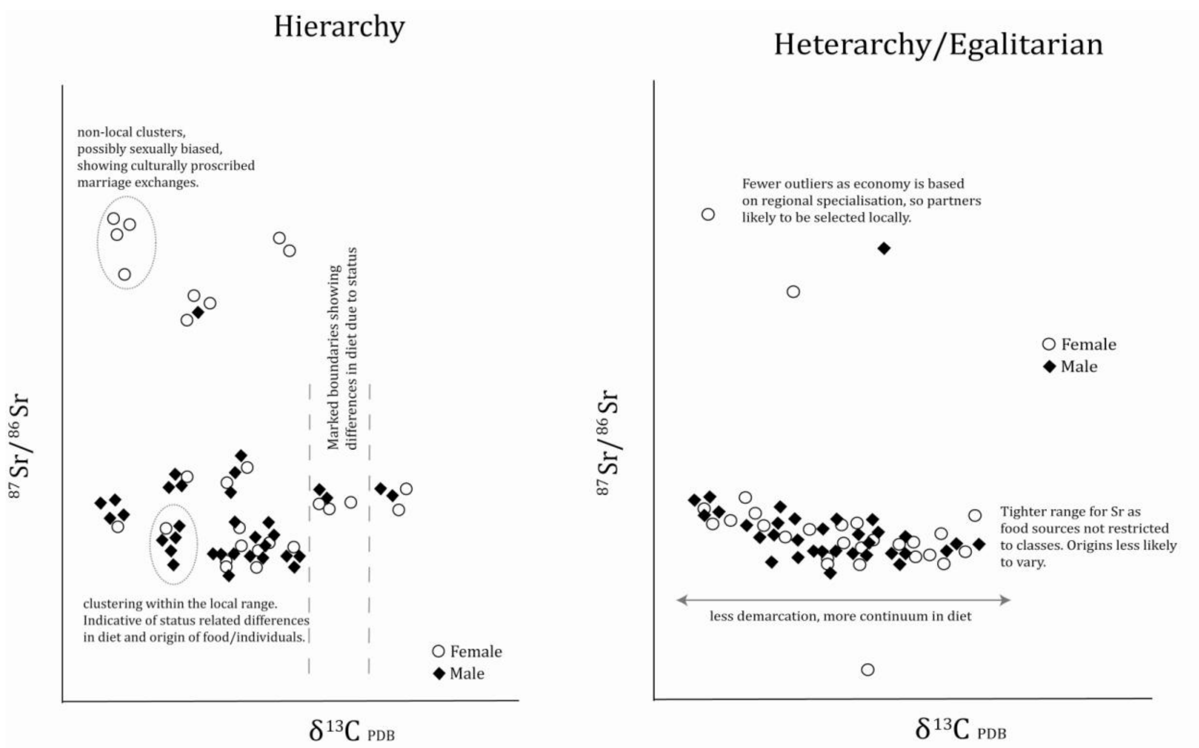

Figure 1: Hypothetical isotopic results representing what we might expect to find under rigid hierarchy and a more flexible heterarchy.

Ban Non Wat: Archaeological and Geological Context

Ban Non Wat, the site of this study, is located in the Upper Mun River Valley of Northeast Thailand (Figure 2, inset). It is one of many moated village sites in the region, making it part of an important archaeological landscape. It was excavated from 2001-2007 by Prof. Charles Higham and Dr. Rachanie Thosarat (Higham & Kijngam, 2009). The site was chosen for analysis because of its size and the number of burials from which samples for isotopic analysis could be taken. The site spans a time period of over 2000 years (Higham & Higham, 2009), during which high levels of social differentiation occurred.

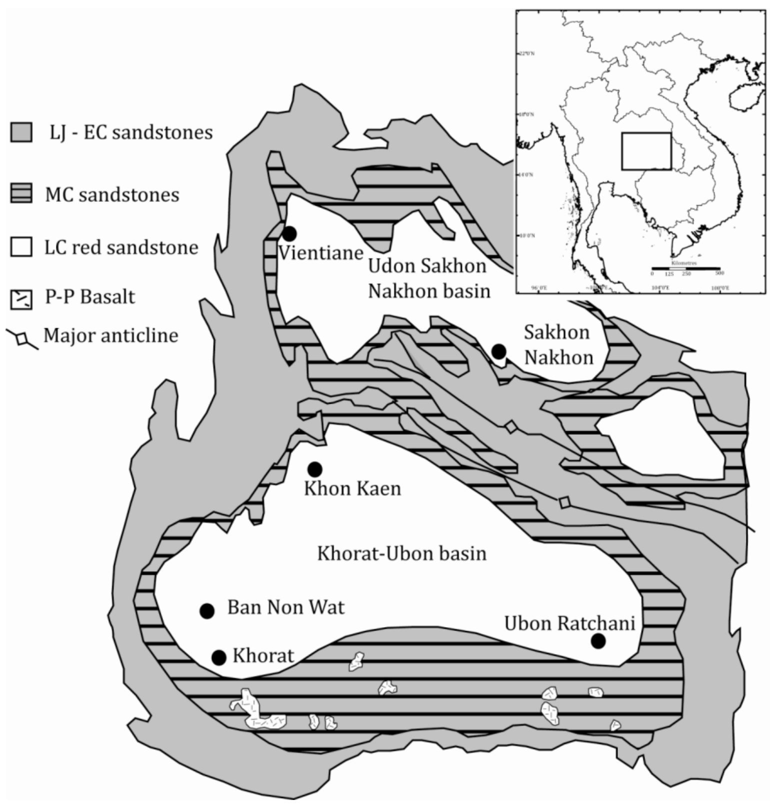

Figure 2: Ban Non Wat and its geological context. LJ = Late Jurassic, EC = Early Cretaceous, MC = Middle Cretaceous, L-C = Late Cretaceous, P-P = Pliocene – Pleistocene.

The cultural sequence of Ban Non Wat begins in the Neolithic. Earliest occupation of the site is dated to 1750BC (Higham & Higham, 2009). There are two phases of Neolithic occupation, with flexed burials at the site possibly predating these Neolithic phases (Higham, 2009). The early phases are overlain by five Bronze Age phases (which begin around 1000 BC). During the Bronze Age we see vast differences in mortuary wealth emerging and areas of the cemetery which seem to be used only for wealthy individuals (Higham & Kijngam, 2012). Iron Age occupation is also evident at Ban Non Wat and begins at approximately 400BC. There are four Iron Age phases identified at the site. Mortuary phases are differentiated on the basis of change in burial practice, orientation, and material culture (Higham & Kijngam, 2009). To date over 650 burials have been excavated from the site of Ban Non Wat.

We also consider the local geology as part of the site's context, as this dictates the local Sr isotope ratio. Bedrock in this area is comprised of a number of sandstone and shale formations ranging in age from the Jurassic through to the late Cretaceous. These formations include red arkose sandstones, which typically have a Sr ratio of > 0.710 (Charusiri et al., 2006), evaporites with a Sr ratio reflecting Cretaceous seawater 0.7071 – 0.7077 (Timofeef et al., 2006), and basaltic outcrops with $^{87}Sr/^{86}Sr$ of 0.7035-0.7038 (Zhou & Mukasa, 1997). The valley will therefore have variable biologically available strontium depending on which of the rock types present are contributing most to the strontium found in soils and water sources. Studies conducted at nearby Noen U-Loke and Ban Lum Khao have yielded conservative local $^{87}Sr/^{86}Sr$ ranges that are essentially identical at both sites, from 0.7096 to 0.7099 (Bentley et al., 2009b; Cox et al., 2011).

Materials and Methods

Strontium, carbon and oxygen isotope analysis was conducted using dental enamel from the burials of Ban Non Wat. The origins of individuals at the site were assessed using strontium isotope analysis ($^{87}Sr/^{86}Sr$). Strontium ratios in human skeletal materials are conveyed from eroding underlying geology, into soils and food sources, and through to the skeleton during mineralisation (e.g. Bentley et al., 2006; Montgomery et al., 2007; Knudson et al., 2008). They therefore provide a geochemical signature, which can differentiate between areas of broadly different geology, though there are non-geological sources of strontium which can cloud the issue, and areas of origin with similar biologically available strontium will be indistinguishable using this technique (Bentley, 2006).

Carbon isotope ratios are well-known indicators of diet, distinguishing broad categories such as C_3or C_4 plants, or marine versus terrestrial foods. $\delta^{13}C$ in dental enamel of BNW individuals should reflect the different contributions of meat or of C_3/C_4 plants to their diets. A diet of pure C_3 plants (e.g. complete reliance on rice agriculture) is estimated to result in $\delta^{13}C$ of -16.1‰ in dental enamel (e.g. Ambrose et al., 1997; King, 2008), whilst C_4 plants and marine foods fall at the other end of the scale, around -4.6‰. $\delta^{18}O$ reflects the composition of water ingested at time of enamel mineralisation and therefore also contains a geographic signature. Previous isotopic studies in Southeast Asia have not so far shown particularly useful differences in oxygen isotope ratio between geographically distinct populations (Bentley et al., 2005; 2007; Krigbaum, 2003), $\delta^{18}O$ data is therefore viewed conservatively, and used mainly to identify outliers indicative of natal settlements of vastly different altitude or latitude.

Strontium isotope analyses were obtained on a ThermoFisher Neptune Multi Collector Inductively Coupled Plasma Mass Spectrometer (MC-ICP-MS) at the Northern Centre for Isotope Analysis and Elemental Tracing, University of Durham. Diagenetic components were removed from chips of enamel weighing between 5-10mg according to Koch et al. (1997), strontium was purified through established methods of chemistry (Charlier et al., 2006). $^{87}Sr/^{86}Sr$ was normalised using repeated measurements of the NBS 987 standard ($^{87}Sr/^{86}Sr$ = 0.710240) in each session of analysis (n=90). The average values for the standard in each session are reported in table 1 of the supplementary data. Total procedural blanks for each batch of chemistry were analysed alongside tooth samples with none exceeding 75pg of Sr, and a mean concentration of 29pg. It should be noted that even the highest concentration blank is insignificant given the very high concentrations of strontium retrieved from the samples.

Carbon and oxygen analyses were obtained using a Thermo Electron MAT253 mass spectrometer in the Stable Isotope Laboratory, Department of Earth Sciences, Durham University. Each analysis used approximately 4.5mg of crushed sample and results were normalised to standards NBS 19 and LSVEC, and were standardised using repeated measurements of internal standard DCS01. Samples were run in 2 periods of analysis, with the running averages of DCS01 being 0.05‰ for $\delta^{13}C$ and 0.03‰ for $\delta^{18}O$ (n=44), and 0.04‰ for $\delta^{13}C$ and 0.02‰ for $\delta^{18}O$ (n=32). Repeat measurements of samples B144 and B263 during analysis gives analytical error of 0.18‰ (1sd). We do not use collagen analysis in this study simply because earlier investigations have shown it is not often preserved at Ban Non Wat (King et al., 2011).

130 adult individuals were sampled from Ban Non Wat, the demographic composition of this sample is laid out in table 1. The second molar was sampled preferentially, representing the period of life between 3-6 years (Hillson, 1996). Table 1 of the supplementary data gives a full list of dental samples used. Eleven domesticated pig (*Sus scrofa*) samples were also analysed. These were used as a proxy for the local signature, as in SE Asia pigs are commonly kept in close proximity to settlements (e.g. Griffin, 1998) and fed scraps reflecting the human diet (Bentley, 2006).

Mortuary Phase	**Male**	**Female**	**Unknown Sex**	**Total**
Neolithic Flexed	4	4	0	**8**
Neolithic 1	5	4	0	**9**
Neolithic 2	6	7	1	**14**
Bronze Age 1	1	1	0	**2**
Bronze Age 2	6	4	2	**12**
Bronze Age 3	11	9	3	**23**
Bronze Age 4	22	26	3	**51**
Bronze Age 5	5	4	2	**11**
Total:	61	59	7	**130**
Faunal remains (*Susscrofa)*	n/a	n/a	n/a	11

Table 1: Sample composition in terms of mortuary phase and sex of individuals analysed.

Results

Isotopic data obtained from the 141 samples (Supplementary Table 1) are plotted with $^{87}Sr/^{86}Sr$ vs. $\delta^{13}C$ (Figure 3), $^{87}Sr/^{86}Sr$ vs. $\delta^{18}O$ (Figure 4), and $\delta^{13}C$ vs. $\delta^{18}O$ (figure 5).

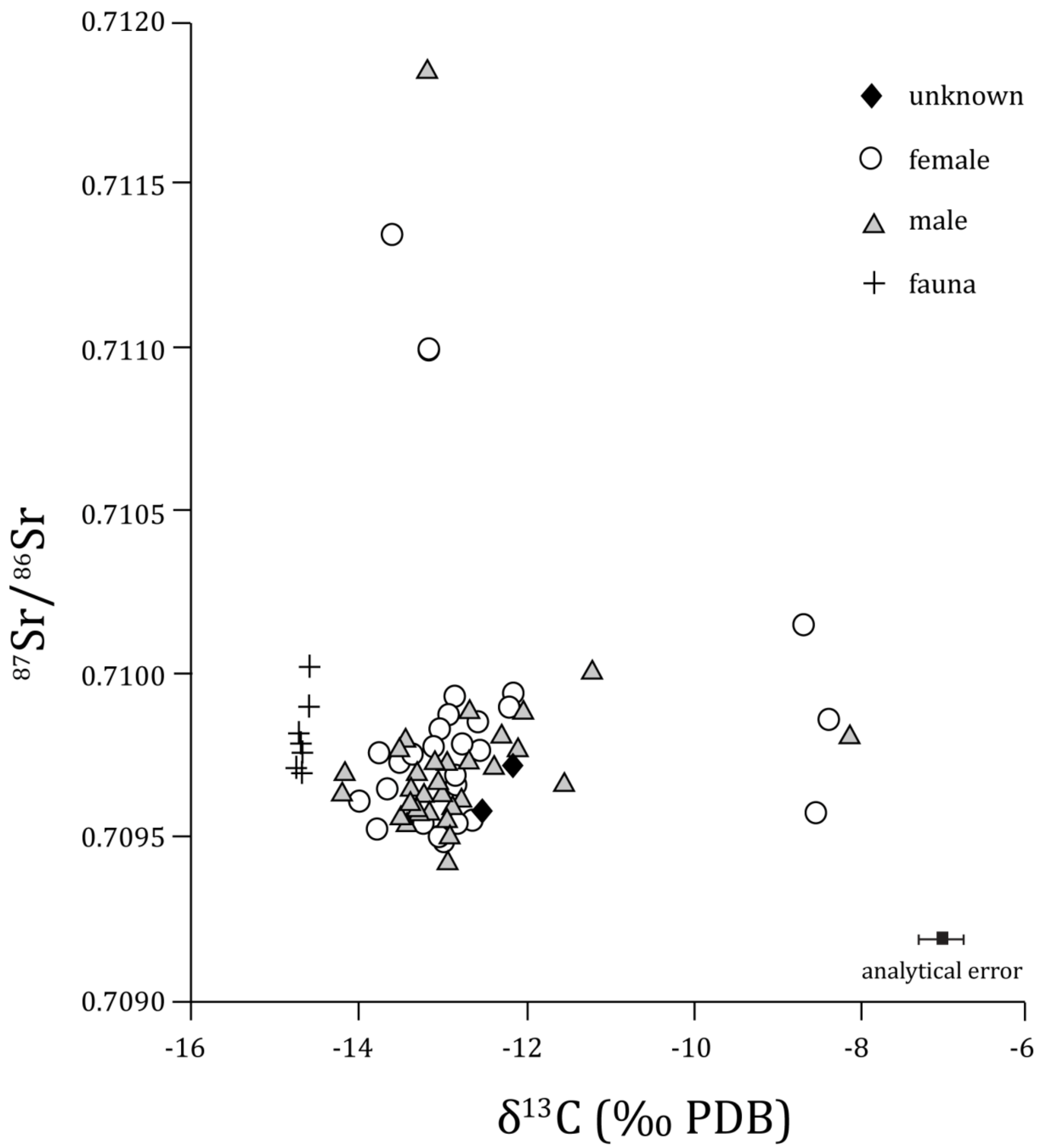

Figure 3: $^{87}Sr/^{86}Sr$ vs. $\delta^{13}C$ isotopic results. Each symbol represents an enamel sample from a different human (or faunal) individual. Circles represent human females, triangles show males, and squares show humans unknown sex. Faunal samples are represented by crosses. Analytical error for Sr analysis is less than the size of the symbol so error bars are not given. Error on carbon isotope measurements is given in error bar (lower right) which represents 2sd either side of a hypothetical measurement.

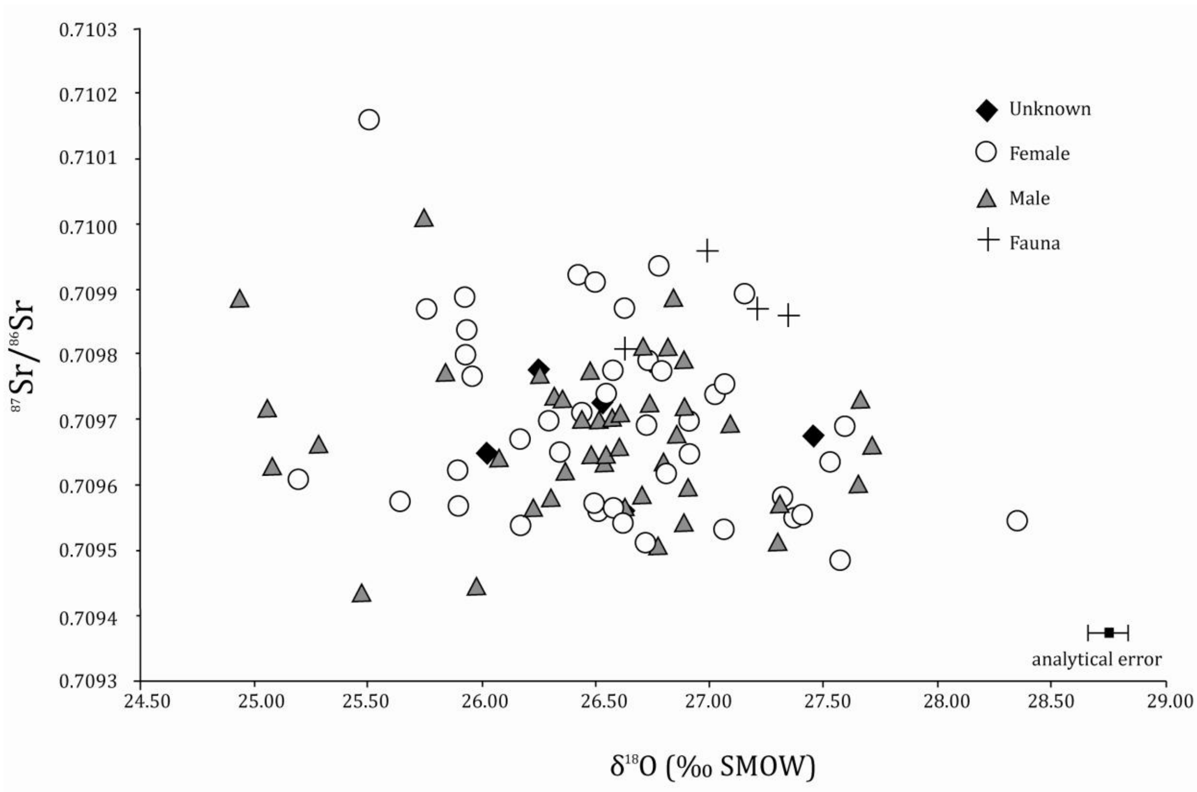

Figure 4: $^{87}Sr/^{86}Sr$ vs. $\delta^{18}O$. Note that 3 Sr outliers with ratios above 0.7110 (shown on figure 3) are excluded from this plot, and one faunal $\delta^{18}O$ outlier at 22.78‰ in order to better show the main body of data. As with figure 3, error on Sr results lies within the symbols used, but 1sd error on oxygen results is given in the lower right of the plot.

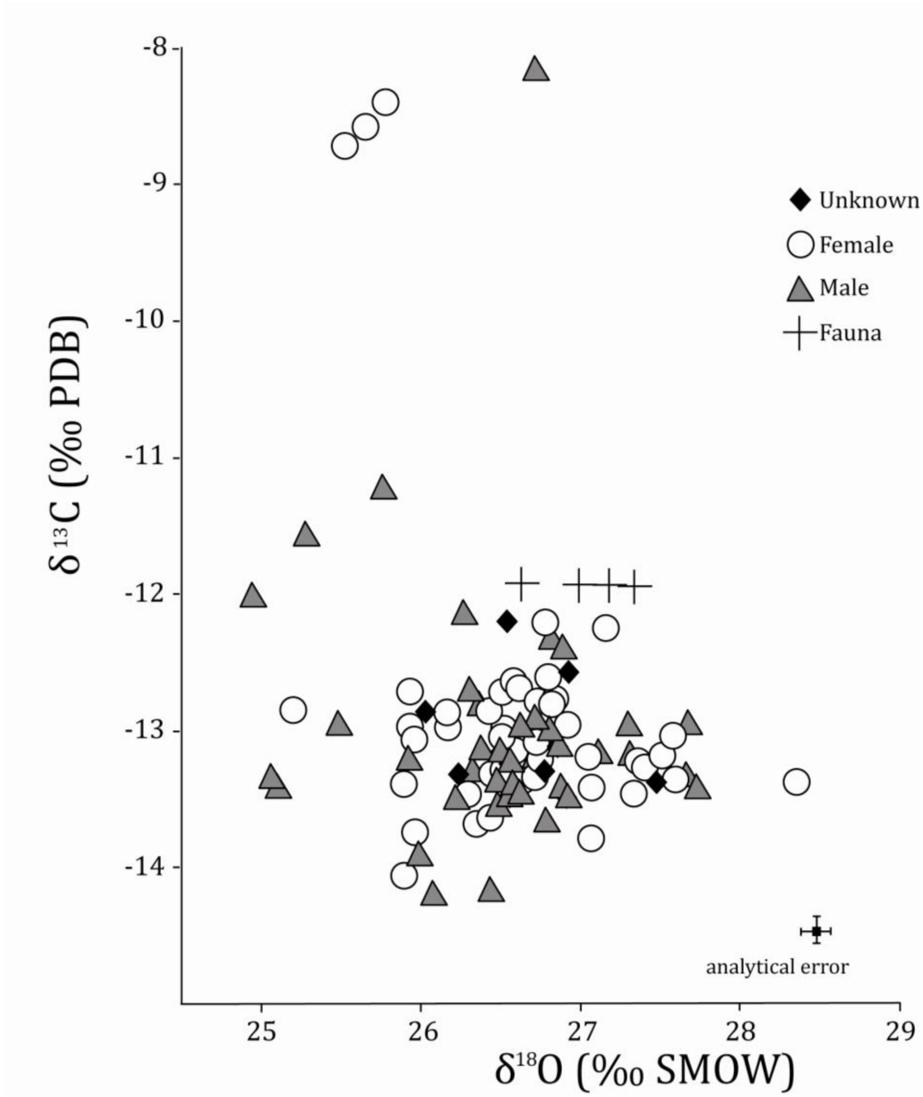

Figure 5: $\delta^{13}C$ vs.$\delta^{18}O$ isotopic results, representation of 1sd error on each datapoint given at the lower right of the plot.

The mean strontium isotope ratio for all human individuals at the site is 0.70972 ± 0.00034 (2s.d. *n* = 130), but the majority (96%) of individuals fall between 0.70940 and 0.71015. This is therefore considered the more conservative local isotopic range. Faunal samples (*n* = 5) give a mean strontium isotope ratio of 0.70993 ± 0.00011 (2s.d.), but the removal of one outlier ($^{87}Sr/^{86}Sr$ = 0.71021, $\delta^{18}O$ = 22.8‰) yields a revised mean value of 0.70990 ±

0.00007 (2s.d.). The clustering of faunal samples within the main body of human isotopic data supports the idea that this is indeed the local range.

There are five obvious outliers present in the strontium isotope dataset; a young male from the Neolithic flexed mortuary phase (B296, $^{87}Sr/^{86}Sr$ = 0.70813), a mid to old female (B153, $^{87}Sr/^{86}Sr$ = 0.71099) and a middle-aged female (B194, $^{87}Sr/^{86}Sr$ = 0.71136) from Neolithic 2, a middle aged adult male from Bronze Age 2 (B97, $^{87}Sr/^{86}Sr$ = 0.71189), and an old female from Bronze Age 4 (B440, $^{87}Sr/^{86}Sr$ = 0.70810). This is shown graphically on Figures 6 and 7, which separate the individuals according to mortuary phase and $^{87}Sr/^{86}Sr$ ratio (Figure 6) and $\delta^{13}C$ (Figure 7).The outliers mentioned above fall well outside of the tight local range seen at Ban Non Wat, and are prime candidates for immigrants from outside of the immediate area.

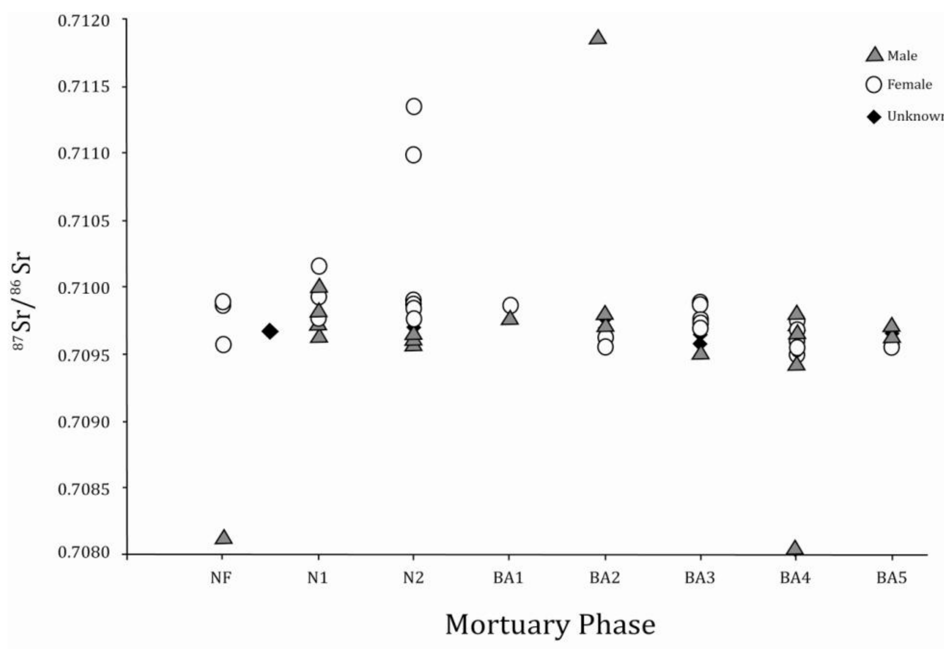

Figure 6: Showing the $^{87}Sr/^{86}Sr$ outliers with reference to mortuary phase and sex.

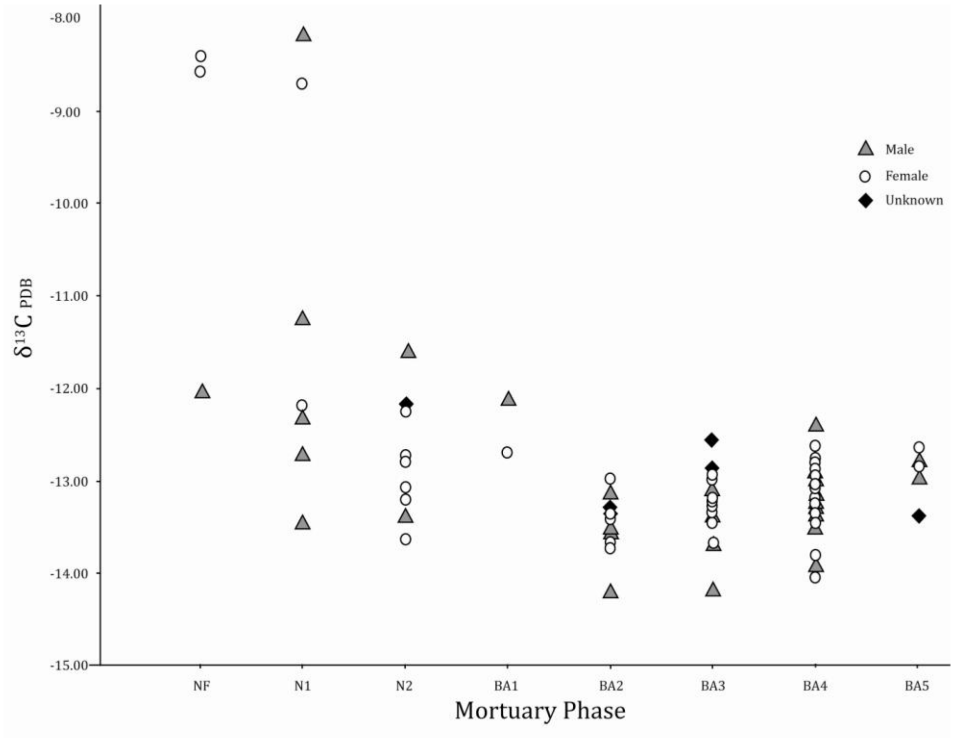

Figure 7: The $\delta^{13}C$ outliers in terms of sex and mortuary phase.

Unfortunately B296 and B440 lacked enough material for carbon or oxygen isotopic analysis to be conducted. The other outliers identified during Sr isotope analysis do not stand out in terms of their carbon isotope ratio, indicating that despite their different origins their diet is likely to have been similar to that of the local population. Carbon isotope analysis does show us that there are individuals who fall within the 'local' Sr bracket who appear to have had very different diets. These are; B461 and B463 (both middle aged females, Neolithic flexed), B292 (young-mid female, Neolithic 1), B255 (young male, Neolithic 1), B28 (old male, Neolithic 1), B304 (middle aged male, Neolithic 2). These individuals are significantly more positive than the main body of data, consistent with more marine/C_4 input into the diet.

There is no significant difference in mean between males and females in $^{87}Sr/^{86}Sr$, $\delta^{13}C$ or $\delta^{18}O$ (p=0.992, 0.585 and 0.423 respectively; 2 tailed *t*-test), or in the variance of these values (p= 0.146, 0.266 and 0.977; Levene's test). There is a significant difference in variance among mortuary phases (p=0.001, ANOVA), but this is likely to be a function of difference in sample size, as post-hoc testing (Tukey's test) shows it is BA4 and BA1 (our largest and smallest subsamples) which have significantly different variance.

If we compare our outlier individuals to others in their mortuary phases in terms of mortuary wealth we find that they are, for the most part indistinguishable from the local population. They do not stand out as being either unusually wealthy or unusually poor, nor do their graves contain items which are considered unusual for Ban Non Wat (table 2).

MP	**Typical**	**Richest**	**Poorest**	**Migrants**
NF	No ceramic vessels, shell beads	B438 – Shell beads, bivalve shells, ceramic vessel, adze head.	B566, 296, 623 – No mortuary offerings	B296 – No mortuary offerings
N2	Few mortuary offerings, one or two globular ceramic vessels.	B25 – 3 ceramic vessels, pig bones and a shell bead.	B71, 286, 303, 436, 547, 561. No mortuary offerings.	B153 – 1 ceramic vessel B194 – 2 ceramic vessels
BA2	Rich burials – multiple ceramic vessels, shell beads and	B105 – 37 ceramic vessels, over 25000 shell beads, 2 marble	B224 – 1 ceramic vessel.	B97 – 4 ceramic vessels, bivalve shells, pig bones

	bangles,	bangles, 3 shell bangles, 22 shell earrings		
BA4	Less than 10 ceramic vessels, rare bangles, no more than 80 shell beads, pig bones	B306 – 21 ceramic vessels, 79 shell beads, 6 pig bones, 3 areas of ochre	B114 – 1 marble earring.	B440- 11 pots, 2 marble earrings, 4 shell beads, 3 bivalve shells and ochre

Table 2: Giving detail of richest and poorest individuals in terms of mortuary wealth, and migrants in each of the phases containing migrant individuals. Information from Higham & Kijngam (2009; 2011; 2012).

Discussion

The results presented here fit well with previous study in the area (Bentley et al., 2009b; Cox et al., 2011), which has found little/no evidence of significant long distance migration. Of the 127 individuals analysed from Ban Non Wat, the majority yielded $^{87}Sr/^{86}Sr$ within the range defined by local domestic pigs, and only 5 had strontium isotope ratios consistent with origins outside of the UMRV. So far, the fraction of probable immigrants during the prehistoric precursors to state society is less than 5% at Ban Non Wat, Noen U-Loke and Ban Lum Khao, and over half of the excavated individuals have been analysed isotopically (Bentley et al., 2009b; Cox et al., 2011 and this study). It therefore seems unlikely that immigration from outside the URMV was the driver of social change. Whilst migrant individuals may be social innovators and influential members of society despite their low numbers, at Ban Non Wat we see no evidence for this kind of social differentiation. The richest burials belong to local individuals, and the mortuary wealth of migrant individuals is in no way unusual.

If a strict hierarchy was present at Ban Non Wat, we might expect some correlation between isotopic outliers and their mortuary wealth, reflecting a fixed status as migrants. We find, however, no significant differences in the mortuary offerings or burial contexts between these outliers and the majority at Ban Non Wat. Burial 153 had only one ceramic vessel, whilst Burial 194 was buried with two pots, which is typical of mortuary offerings in Neolithic 2. Individual 194 was buried tightly wrapped which differs from her contemporaries, but there does not appear to be any standardised way of preparing the dead for burial during this period so no conclusions can be drawn from this (Harris, 2010). Burial 97 was buried with 4 ceramic vessels, pig bones and mollusc shells, making him one of the poorer individuals in BA2, but this phase does have the largest discrepancy between individuals in terms of wealth. Burial 440 was buried with a wealth of mortuary goods including 11 pots, marble earrings, shell bangles, beads and ochre, but for Bronze Age 4, where we see much more mortuary wealth, this is not unusual (Higham & Kijngam, 2009). She was buried loosely wrapped, as were a considerable number of her contemporaries (Harris, 2010). Burial 296 cannot be commented on as the skeleton did not fully fall within the excavation area, and only the cranium and forearms are present for analysis. This lack of distinction for any of the migrant individuals indicates assimilation into the society of Ban Non Wat, and implies that status was unrelated to local/non-local origins.

In fact when we look at the possible origins of the ‘migrants’ we see that burials 153, 194 and 97, have $^{87}Sr/^{86}Sr$ ratios near 0.711 and are within the range we would expect to see in the Songkhram Basin (Bentley et al., 2005), north of the UMRV, but still within the Khorat

Plateau. The two outliers which fall around 0.708 could be linked to many geological sources, but likely candidates are the evaporite formations, which are present within the sandstones of the region, and stretch across the Khorat Plateau. In other words even the few, definitive immigrants among the Ban Non Wat sample may well be from within the Khorat plateau.

This should, perhaps, be unsurprising as both hierarchical and heterarchical models of social evolution do not necessarily involve external input. Heterarchical theory in particular focuses on the idea of craft specialisation "within a community based mode of production organisation" (White & Pigott, 1996: 151) during social evolution. It seems more likely that exogamous marriage partners would be chosen from nearby settlements, as migration is most likely to occur over short distances between habitually interacting social groups (e.g. Anthony, 1997; Fix, 2004; Lewis, 1982). This is likely to have been the case in prehistory, and it seems far-fetched indeed to assume that the settlements of the UMRV were socially and reproductively isolated from one another. We find continuity in terms of material culture and mortuary traditions between Ban Non Wat and contemporaneous phases of nearby sites (Higham & Kijngam, 2011), which suggests contact and/or trade. There is no reason to suggest that this did not also include marriage exchanges.

In this study we have not tested whether this pattern continues into the Iron Age, this is an area for future research. Evidence at Noen U-Loke (Cox et al. 2011; Tayles et al., n.d.) suggests that it might, though O'Reilly (2001) proposes that there may be a substantial change in social organization in the Iron Age, and it is possible that this involves more migration to the area.

With the possibility of migrant impact on social evolution significantly reduced, we now turn to what the isotopic results can tell us about the structure of indigenous society. Neither of our idealised scenarios representing hierarchy and heterarchy (figure 1) fit our results perfectly. We do have a group which is obviously separated from the main body of carbon isotope data, which could be interpreted as a demarcated difference in diet under hierarchy. These individuals, however, are not separable in terms of mortuary wealth. The majority of these individuals are also from the early Neolithic phases of the site, where status differentiation does not seem to be present (Higham, 2011). Instead we think it more likely that this group represents early, short-distance migrants to the site whose childhood involved consumption of C_4 foodstuffs, and intend to fully explore dietary differences in later research.

If we consider the main body of isotopic data we find it contains no obvious clusters. We would consider clustering evidence of separation of groups due to inherent status differences. Instead we see a rough continuum of dietary isotope values and a tight range of Sr isotope values. This is more consistent with the model of heterarchy. This is by no means conclusive evidence for a lack of hierarchy in the region but, combined with archaeological evidence, it certainly indicates that social evolution cannot be fully described by Service's model of social progression.

Conclusion

Isotopic work in the UMRV has shown that migrant individuals likely had very little impact on society in the region. In this study we have attempted to use isotopic results to add to the body of data available on social structure and development in the region's prehistory. We come to the conclusion that the evidence from the isotopes cannot support the idea of a strict hierarchy involving proscribed dietary differences between the classes and established marriage exchanges with distant sites. This does not preclude the idea of hierarchy altogether, but means if it is present it is not as rigid as traditional models infer. The evidence does not, however, oppose the idea of heterarchy in the area, a flexible form of social organization, with status assignation based on a number of factors including personal merit.

15. Manuscript Two

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TITLE: Mixed economies after the agricultural revolution in Southeast Asia?

AUTHOR(S): Charlotte L King, Alex Bentley, Nancy Tayles, Geoff M Nowell, Colin G Macpherson, Una Strand Viðarsdóttir, Robert Layton.

Mixed economies after the agricultural revolution in Southeast Asia?

Charlotte L. King, R. Alexander Bentley, Nancy Tayles, Una Strand Viðarsdóttir, R. Layton, Colin G. Macpherson, Geoff Nowell

Abstract

Archaeological evidence from Europe indicates a rapid transformation of society with the introduction of agriculture. As this 'revolutionary' pattern is often assumed in Southeast Asia, with early rice agriculture present from around 2000BC, inter-site variation in subsistence strategy is not well-investigated. Here we measure carbon, oxygen and strontium isotopes from closely-spaced prehistoric villages of the Upper Mun River Valley in Thailand, and find evidence for significant differences in both reliance on rice agriculture and water sourcing. We suggest that the introduction of agriculture in Southeast Asia was more heterogeneous than conventionally assumed, and that mixed economies were just one aspect of significant levels of social diversity during prehistory.

Introduction

In Neolithic Europe, the introduction of agriculture produced a rapid and complete shift in social organisation and subsistence strategy (Bocquet-Appel, 2011; Cavalli-Sforza, 1996; Bellwood & Renfrew, 2002). In Neolithic Southeast Asia, however, rural settlements relied on rice or millet agriculture to some degree (e.g. Glover & Higham, 1996), but their commitment to agriculture appears variable across regions (e.g. White et al., 2004; Douglas & Pietrusewsky, 2007).

In Thailand gradual agricultural uptake has been suggested, and inter-site differences in material culture also indicate cultural diversity (White, 2011). There is evidence for differential involvement in trade of exotic items, for instance *Trochus* bangles are present in the site of Ban Na Di but contemporaneously absent at nearby Ban Chiang (White, 1995). Differences in involvement in production circuits has also been observed in Bronze Age southern Thailand (White & Hamilton, 2009), while Western Thailand appears to have been bypassed entirely by Bronze technology (Glover, 1991). Study of mortuary ceramics at Ban Chiang by White & Eyre (2011) has also highlighted the possibility of sub-regional stylistic and technological groupings, which may be related to territorial subdivisions.

In addition to this material culture evidence, here isotopic evidence is presented showing *dietary* variation between agricultural sites in Southeast Asia. The study focusses on the Upper Mun River Valleyof northeast Thailand (UMRV), a region of substantial population nucleation and agricultural intensification during the first millennium BC. Higham & Kijngam (2012) have reported vast differences in mortuary wealth between contemporary phases at the sites of Ban Non Wat and Ban Lum Khao (Figure 1), with all individuals at Ban NonWat having a greater number of grave offerings than the 'richest' at nearby Ban Lum Khao. This difference in wealth between the sites is given as evidence of marked difference in access to prestige materials and effort expended on mortuary ritual (Higham & Kijngam, 2012).

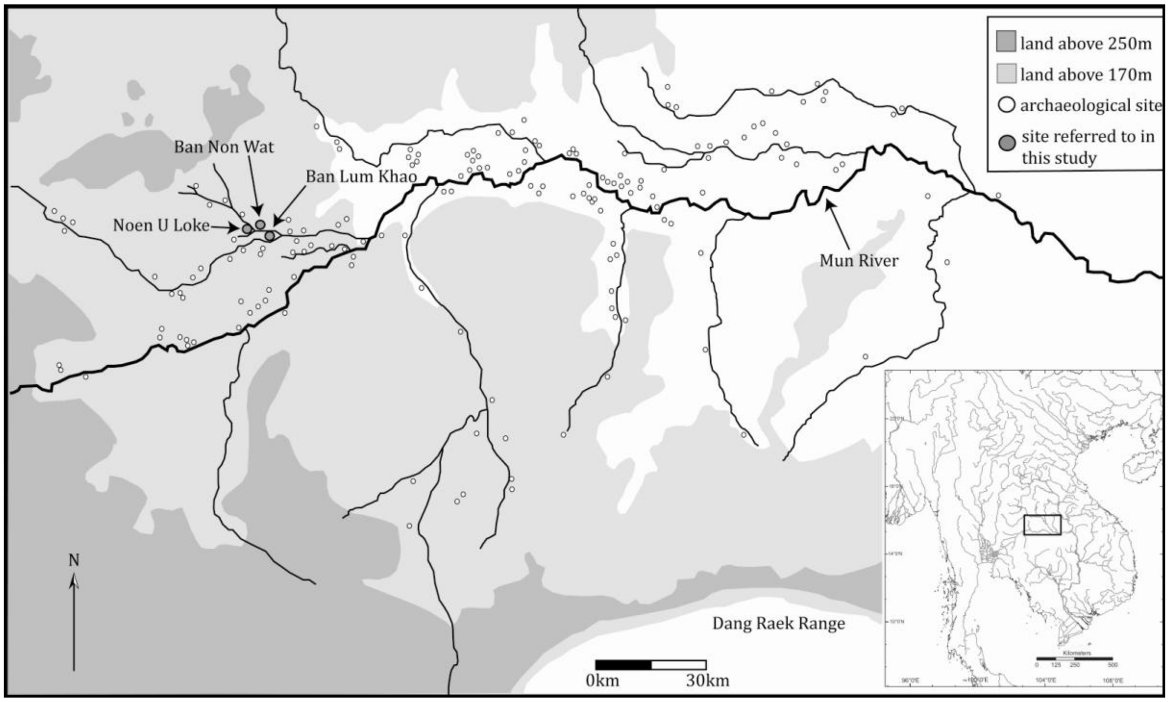

Figure 1: Map of the study region (after Higham & Kijngam, 2009)

With much material now excavated in the UMRV, there is an opportunity to align these material culture differences with isotopic evidence for diet. In this study isotopic analysis ofdental enamel from sites of the UMRV was conducted to test whether or not small-scale differences in diet, as well as material culture are present between sites.

In order to accurately reflect the complexity of resource use in human society we test several hypotheses regarding observed dietary differences, evaluating them using ethnographic data. We draw upon evidence from modern Southeast Asian rice agriculturalists, as well as those without a rice-based economy elsewhere in the world. These were used as analogies due to their similar social structures and subsistence behaviours to those proposed for prehistoric Southeast Asia. Ethnographic evidence shows that mixed economies are common and that agricultural communities in the modern world often have substantial differences in dietary reliance on wild vs. domesticated crops (Layton et al., 1991; Lourandos, 1980; Stark et al., 2000), and may even form symbiotic relationships with hunter-gatherers (Headland & Reid 1989; Spielmann & Eder 1994; Turnbull, 1965). Dietary differences may be due to marginalisation of certain communities, with lower status resulting in lack of access to resources (Ames 2010; Arnold, 1995). Wealth differences are not, however, the only explanation for dietary variation, the reinforcement of cultural identities is often equally important in ethnographically observed food choice (Hodder, 1979; Nelson et al., 2011).

Regardless of the reasoning behind different resource use, it is clear that it is diversity not uniformity, which characterizes the Southeast Asian Neolithic. This compounds the idea that the pathway to Neolithisation in this region was very different from the swift transition observed in Europe.

Materials and Methods

(a) *Archaeological samples*

Our study encompasses three sites within a 10km radius in the UMRV: Ban Non Wat, Ban Lum Khao and Noen U-Loke. Primary data come from the larger site of Ban Non Wat, comparative isotopic results are taken from previously published studies at Noen U-Loke (Cox et al., 2011) and Ban Lum Khao (Bentley et al., 2009). The comparative studies were all conducted at Durham University, using the same procedures and equipment as described here. The locations of the sites are given in Figure 1.

The most comprehensively excavated of the three sites is Ban Non Wat. Here an area of $892m^2$ was excavated over seven seasons, yielding 637 human burials, from which our primary isotopic sample is taken. Identified through stratigraphy, mortuary practice, and material culture, the cultural sequence of Ban Non Wat begins in the Neolithic, though hunter-gatherer occupation may predate this (Higham & Kijngam, 2009). With the earliest occupationdated to 1750BC (Higham & Higham, 2009), there are three identified phases of Neolithic occupation (Higham & Kijngam, 2011), overlain by five Bronze Age phases (which begin around 1000BC). The Iron Age occupation of Ban Non Wat is dated to approximately 400BC.

Discrepancy in mortuary wealth between individuals is notable, particularly in the second Bronze Age mortuary phase, where ‘super-burials’ are juxtaposed with less wealthy individuals, and interpreted as evidence for a ruling elite (Higham & Kijngam, 2009; 2012). Interestingly, these differences in mortuary wealth decrease through the rest of the Bronze Age and into the Iron Age, perhaps indicating that an inflexible hierarchy was not in place at Ban Non Wat (White, 1995; O’Reilly, 2003).

Here carbon isotope results from 69 dental enamel samples from the phases at Ban Non Wat are presented (details in Supplementary Table 1) and compared with results from the contemporary phases of two sites within 20 km of Ban Non Wat (Figures 1 and 2); 35 samples from Noen U-Loke (Cox et al., 2011), and 26 samples from Ban Lum Khao (Bentley et al., 2009).

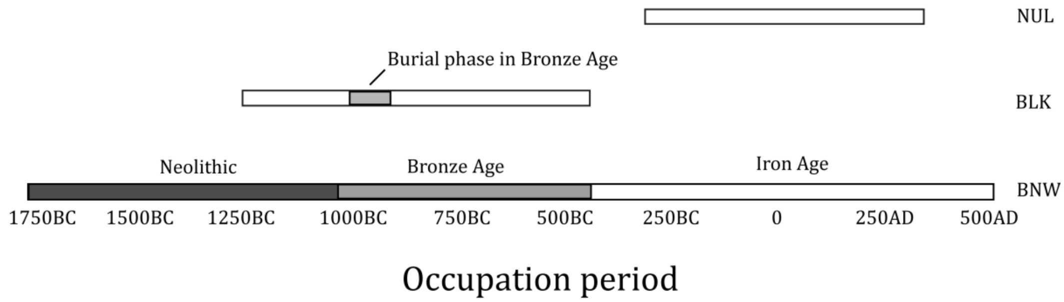

Figure 2: Chronology of Ban Non Wat compared with Noen U-Loke and Ban LumKhao (Higham et al., 2005; 2007; Higham & Kijngam, 2009) BNW and NUL have burial phases spanning their occupation. Excavated BLK burials are restricted to the Bronze Age.

(b) *Assessment of wealth from mortuary goods*

To evaluate social differences at Ban Non Wat, we follow Higham & Kijngam (2009; 2012) by using both quantity and nature of grave goods as proxies (also Binford, 1971). We will consider the quantity of bronze and other metal artefacts, ceramic vessels, and exotic goods such as shell or glass beads, as a ‘crude measure’ of wealth (Higham & Kijngam, 2012: 451). We make no assessment of quality.Of course, mortuary wealth might reflect factors other than social differences (Brown, 1995; Ucko, 1969; Robb et al., 2001), but our objective is simply to detect differences in diet correlatedwith broader social categories in these early agricultural societies.

(c) *Background to Isotopic Analysis*

Diet is commonly studied archaeologically through the proxy of carbon and nitrogen isotopes in skeletal material. In this study only carbon isotopes in dental enamel were analysed because collagen, containing organic carbon and nitrogen, is not well preserved at Ban Non Wat (King et al., 2011).

The theory behind carbon isotope analysis as a dietary proxy has been explained in depth elsewhere (Hobbie & Werner, 2000; Vogel, 1993). Broadly speaking, carbon isotopes reflect the photosynthetic pathway of plants consumed (C_3 vs. C_4). It is therefore possible to separate individuals consuming C_4 crops, such as maize and millet, from those subsisting on more common C_3 plants, such as rice and wheat (e.g. Schoeninger & Moore, 1992; Schwarcz & Schoeninger, 1991). Marine resources also have a characteristic carbon isotope signature (Schoeninger et al., 1984), but their use is considered unlikely due to the inland location of the UMRV. Within a predominantly C_3 diet, $\delta^{13}C$ variability is small and unlikely to identify specific diets, but does yield broad information on the food groups being consumed by an individual.

Strontium isotope ratios are used here to identify any obvious immigrants from outside the UMRV. $^{87}Sr/^{86}Sr$ ratios are fundamentally derived from the underlying geology of the area in which an individual sources their food and, therefore, provide a signal of geographic origins (Bentley, 2006). The results of strontium isotope analysis at these sites are discussed elsewhere (King et al., *in review*; Cox et al., 2011; Bentley et al., 2009).

(d) *Isotopic Analysis*

Material for isotopic analysis was preferentially taken from the 2^{nd} molar which gives a dietary signal from childhood – approximately 3-6 years of age (Hillson, 1996). If the 2^{nd} molar could not be sampled then other teeth were chosen based on the principles set out in King et al. (*in review*). Analyses were conducted on a chip of dental enamel weighing between 5 and 10mg according to established procedures (King et al., *in review*; Koch et al., 1997) at the Stable Isotope Laboratory, Department of Earth Sciences, Durham

University (carbon isotopes) and the Northern Centre for Isotope Analysis and Elemental Tracing, University of Durham (strontium isotopes).

Carbon and oxygen isotope ratios, measured in the carbonate portion of tooth enamel, were normalised to international standards NBS 19 and LSVEC. Repeated measurements of internal standard DCS01 were used to constrain temporal drift in measurement. Powdered samples were run in 2 periods of analysis, with the standard deviation of DCS01 measurements in each of these periods being 0.05‰ for $\delta^{13}C$ and 0.04‰ in each (2s.d.). Analytical error was calculated using repeat measurements of selected samples (B144 and B263) as 0.18‰ (1sd). Strontium isotope samples were run in 9 batches and normalised using repeated measurements of the NBS 987 standard ($^{87}Sr/^{86}Sr$ = 0.710240), average NBS standard values for each batch of analysis are given in Supplementary Table 1.

Results

Supplementary Table 1 presents the full isotopic results, listed along with grave goods for each sampled burial, while Table 1 gives the mean $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ for females and males at BNW, BLK and NUL.

	BLK	**BNW phases contemp to BLK**	**NUL**	**BNW phases contemp to NUL**
$\delta^{13}C$ (‰ PDB)				
Both sexes	-14.0 (*n=25;* 2s.d.= 0.77)	-13.2 (*n=44;* 2s.d.=1.05)	-13.6 (*n=34;* 2s.d.= 0.76)	-12.7 (*n=24;* 2s.d.=1.08)
Males	-13.9 (*n= 10;* 2s.d= 0.84)	-13.3 (*n=18*; 2s.d.=1.33)	-13.7 (*n=17;* 2s.d=0.75)	-12.9 (*n=5;* 2s.d. = 1.62)
Females	-14.0	-13.2	-13.5	-12.8

	(*n=15;* 2s.d.= 0.64)	(*n=22;* 2s.d.=0.81**)**	(*n=14;* 2s.d.=0.75)	(*n*=10; 2s.d.=1.18)
$^{87}Sr/^{86}Sr$				
Both sexes	0.7096 (*n=26*; 2s.d.= 0.0009)	0.7098 (*n=42;* s.d.=0.0004)	0.7097 (*n*=35; s.d.=0.0005)	0.7097 (*n*=25; s.d.=0.0003)
Males	0.7095 (*n=11;* 2s.d.= 0.002)	0.7098 (*n=17;* 2s.d.= 0.0001)	0.7098 (*n=17;* 2s.d. = 0.0002)	0.7098 (*n*=7; 2s.d.=0.0002)
Females	0.7098 (*n=14;* 2s.d.=0.0004)	0.701 (*n=22*; 2s.d.=0.001)	0.7097 (*n=14;* 2 s.d.=0.0002)	0.7097 (*n*=11; 2s.d.=0.0003)

Table 1: Mean $\delta^{13}C$ and strontium isotope ratios with 2sd and number of samples analysed following the means. The BNW results are divided into two subsets, those contemporaneous with BLK, and those contemporaneous with NUL, in order to avoid comparing results which are temporally disconnected.

Within the BNW sample, the two phases comparable with BLK and NUL have similar carbon isotope ratios, with later phases having on average higher $\delta^{13}C$ values than the earlier phases (p=0.002). Figure 3 illustrates the difference in values between comparable phases.

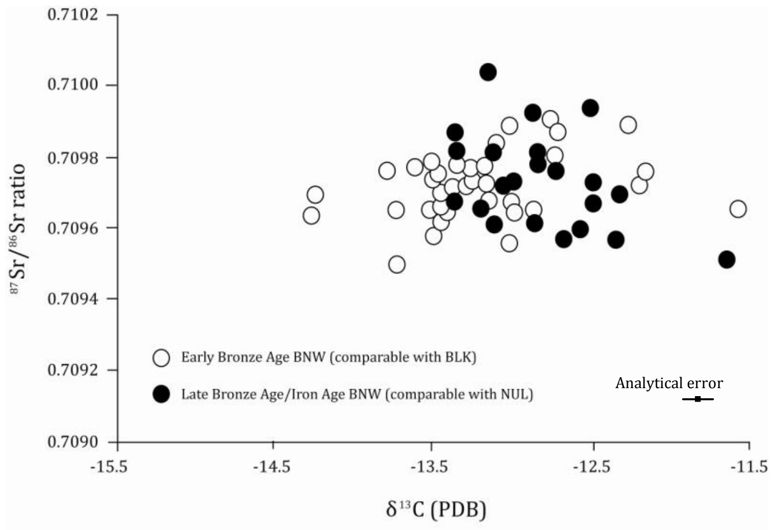

Figure 3: Change through time in C isotope ratios at BNW. White circles are those results from burials that are contemporaneous with BLK. Black circles are contemporaneous with NUL.

Comparisons of carbon isotope data between sites are presented in Figures 4a (BNW vs. BLK) and 4b (BNW vs. NUL). Of the three sites, BNW has the highest mean $\delta^{13}C$ value, and BLK has the lowest (Table 1). Lower $\delta^{13}C$ values are indicative of a more C_3 plant dominated diet. All of the $\delta^{13}C$ results from this study are consistent with C_3 crop use, but the higher values at Ban Non Wat may indicate lesser reliance on C_3 crops and more supplementation of the diet by other food sources.

The sites show significantly different carbon isotope results ($p<0.01$ for both sets of data) but no significant difference in strontium isotope ratio (t-test $p>0.1$).

The range of individual measurements of $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ within each site is remarkably similar (0.0005 and 1.5‰ respectively), despite the differences in where these values fall on the spectrum i.e. $\delta^{13}C$ values of Ban Lum Khao and Ban Non Wat values fall within a 2‰ range, but this range is -13.1‰ to -15.1‰ for BLK, and -12.2‰ to -14.2‰ for BNW.

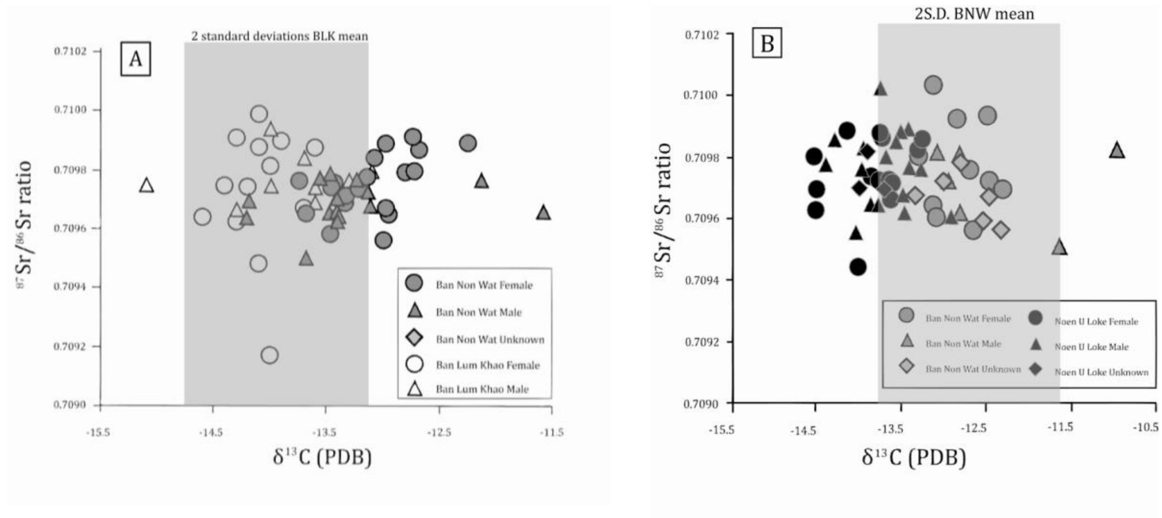

Figure 4: Difference in carbon isotope results (‰ PDB) between (a) Early Bronze Age phases of BNW and BLK samples, and (b) Late Bronze Age and Iron Age samples from BNW and NUL. In both cases BNW samples possess higher $\delta^{13}C$ (‰) and there is no distinction between males and females at each site.

Figures 5a and 5b correlate the number of mortuary offerings with carbon isotope values in order to assess whether or not dietary differences are related to underlying status/material culture.

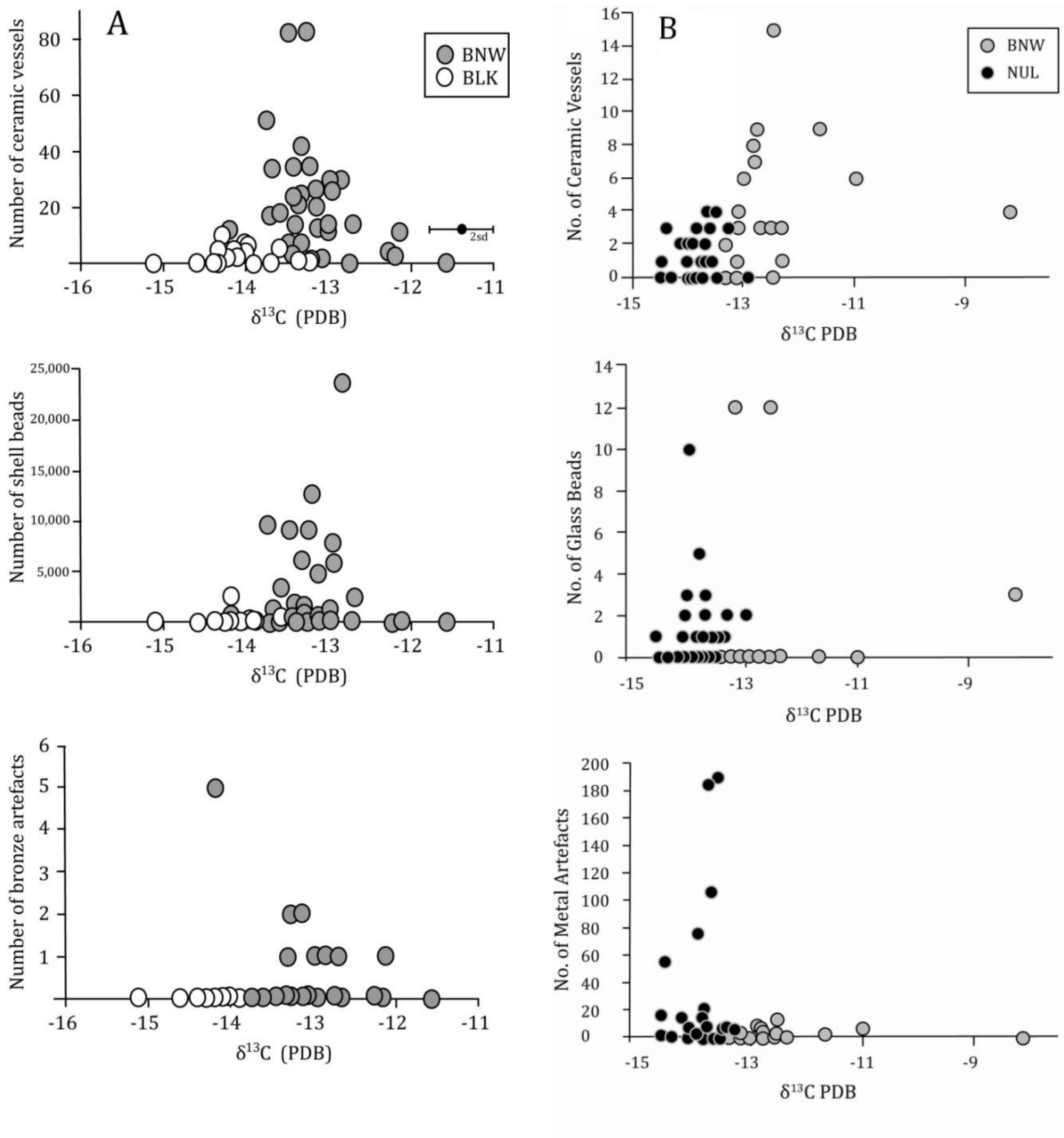

Figure 5: Number of ceramic vessels (top), shell/glass beads (mid) and bronze/metal artefacts (bottom) associated with burials from (a) Early Bronze Age Ban Non Wat (grey) and Ban Lum Khao (white), and (b) Late Bronze Age and Iron Age burials from Ban Non Wat (grey) and Noen U-Loke (black). Plotted against $\delta^{13}C$ (‰ PDB).

Figure 5a indicates a correlation between a higher number of mortuary goods at Ban Non Wat and less reliance on C_3 crops, but comparison with NUL (figure 5b) shows this is not a pattern that persists into the Iron Age, as Noen U-Loke has greater numbers of mortuary goods, but more reliance on rice.

Discussion

(a) Differences in carbon isotope values

The results of this study show that, while the residents of all sites in the valley had a diet dominated by C_3 plants such as rice, the extent to which they relied on these crops differed significantly. This suggests that no uniformity in the uptake of, or level of reliance on, rice agriculture during prehistory.

While agriculture is usually considered to be a universally accepted 'package', modern ethnographic observation indicates that, despite having knowledge of agricultural practices, many groups choose to remain hunter-gatherers or horticulturalists (Hutterer, 1983; Turnbull, 1965). It is probable that in Southeast Asia the uptake of agriculture was not as rapid as in Neolithic Europe, with hunting, gathering and horticultural systems persisting to a greater or lesser extent depending on the site (as in White, 2011). Palynological study in the UMRV has previously suggestedthat there were local variations in the level of human land management, crop use and vegetation (Boyd & McGrath, 2001).

Based on archaeological and ethnographic evidence we identify several possible reasons for these observed differences in resource use. These are evaluated below:

i)Differences in wealth between the sites:

All three sites studied have a diet dominated by C_3 crops, probably rice. The higher δ^{13}Cvalues at Ban Non Wat indicate that diet is supplemented with either C_4 crops or meat. If greater consumption of meat is the cause of this difference then it is plausible that dietary variation is linked to underlying wealth differences between the sites.

Sources of fat are highly valued in subsistence economies as they are by far the most efficient providers of energy (Mead et al., 1986). Game, therefore, ranks high in an optimal forager diet (Layton et al., 1999). The importance of meat means that the consumption of higher proportions or better cuts of meat is often the prerogative of high status individuals, and this has been observed archaeologically in geographically and culturally disparate groups (see: van der Veen, 2003 for a review). The use of meat as a prestige food has been observed ethnographically in Southeast Asia, particularly in the tribes of highland Myanmar and northern Thailand (Leach, 1954; Falvey, 1977), and is also common worldwide (Sahlins, 1963; Århem, 1989). On the other hand, reliance on a carbohydrate staple crop has associations with poverty. This has been noted in present-day societies (e.g. Ruel et al., 2010), and reported in isotopic studies of archaeological populations (e.g. Ambrose et al., 2003).

The links between diet and status worldwide mean it is plausible that dietary differences between the sites of the UMRV may be evidence of differences in wealth between the settlements. Wealth discrepancies are evident between BNW and BLK, as figure 5 shows. The individuals of Ban Lum Khao have both greater reliance on rice and far fewer mortuary offerings and exotic goods than those at Ban Non Wat. Superficially then, this seems to suggest that the higher carbon isotope values at Ban Non Wat may be evidence for difference in status, and have significant implications for interpretation of interaction patterns across the landscape. Inter-site wealth differences may indicate patron-client or centre-periphery relationships (cf. Wolf, 1966; Rowlands, 1987), or alternatively limitations of trade and exchange (e.g. Bauer & Agbe-Davis, 2010).

This argument is only valid, however, if samples analysed are unbiased i.e. both the richest and the poorest of the populations are represented in each isotopic sample. This is unlikely to be the case. The excavation area at BLK was small and limited to the edge of the site to avoid the existing settlement, potentially biasing the sample. BNW, however, has been comprehensively excavated to include almost sections of the site.

Other evidence against this hypothesis includes the fact that, if rice consumption truly was related to status, a constant correlation would be expected between mortuary wealth and diet. This does not appear to be the case. While BNW is ‘richer’ than BLK, and has less reliance on C_3 crops, it seems the opposite is true in the case of BNW and NUL (figure 5). Wealth differences alone, therefore, are unlikely to account for the dietary variation seen.

(ii)Cultural preference

Archaeological research in Asia has tended to focus on the economic implications of rice cultivation. There is, however, increasing recognition that social values may have affected subsistence strategy (e.g. Smith, 2006; Fuller et al., 2004). Food choice and access not only reinforces status, but can also be used to create a sense of unity and identity (Smith, 2006). Different cultural groups living in close proximity may, therefore, choose to assert their identity through dietary preferences.

There is certainly growing archaeological evidence for cultural sub-regions in Thailand. White & Eyre (2011), for instance, suggest this was occurring in the Ban Chiang area, lying to the north of the UMRV. Here distinctly different ceramics are present at Ban Chiang and nearby Ban Na Di, and there are differences in faunal and ceramic inclusion in mortuary contexts. The situation in the UMRV may be analogous to this; previous work has suggested centralisation of power, and focus on household production units (O'Reilly, 2003), which would lend itself to cultural diversity. Further archaeological support for this scenario includes variability in ceramic vessel fabric within the UMRV (Voelker, 2007) and differences in ceramic inclusion in mortuary contexts, (Higham & Kijngam, 2012).

Differences in group perception of the importance of rice is also supported by the inclusion of rice in burials in Iron Age Noen U-Loke, but the absence of rice in mortuary ritual at contemporary Ban Non Wat (Higham et al., 2007). Cultural preferences, therefore, may go some way towards explaining differences in reliance on rice.

(iii) Differences in location on the floodplain

It has been ethnographically observed in areas such as the Democratic Republic of the Congo (Turnbull, 1965) that clearance around villages for farming leads to a lack of game around the settlements, making supplementation of the diet with hunting very rare. It is possible that the creation of field systems within the UMRV cut off access to game, with only those sites closer to the edge of the floodplain having access to forest resources.

The sites of this study are close together, but they do occupy slightly different regions of the valley. BNW and NUL are closer to the edge of the floodplain than BLK (figure 6), and more likely to have had access to forest resources such as game or non-domesticated plants.

Pollen cores support this, showing that forest species were present close to Ban Non Wat (Boyd & McGrath, 2001) and faunal analysis at BNW (Higham & Kijngam, 2009; 2011) indicates that the people of Ban Non Wat were supplementing their diet with wild meat such as turtle, deer, and wild oxen.

The lesser exploitation of wild resources at NUL, despite proximity to the forest, supports the hypothesis that at NUL rice was accorded greater *cultural* importance, despite other food sources being available.

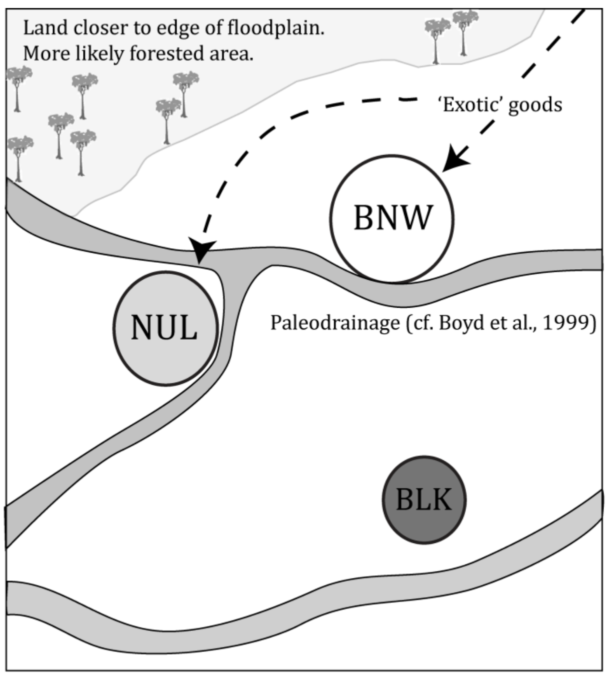

Figure 6: Summary diagram showing differences in reliance on rice (white = less, dark grey = more), positions on paleochannels (from Boyd et al., 1999), and probable direction of forest during prehistory (Boyd & McGrath, 2001).

(iv)The presence of C_4 crops

The highercarbon isotope values at BNW may not reflect supplementation of the diet by meat but instead C_4 crops, such as millet. This scenario cannot yet be confirmed as there is currently no evidence for C_4 crops in the UMRV (Castillo, 2011). Macrofossil (Weber et al., 2010) and phytolith (Kealhofer & Piperno, 1994) analysis conducted in nearby valley systems such as the Khao Wong Prachan valley to the west however, indicate the presence of millet (C_4) from around 2000BC, with rice appearing later in the sequence. The possibility of millet in the UMRV cannot, therefore, be completely discounted.

(b) *Different pathways to Neolithisation*

Overall the isotopic variation between the sites of the UMRV indicates differences in reliance on rice, even within the same archaeological landscape. It seems likely that these differences were based on cultural preferences, rather than status. Such a conclusion is supported by the symbolic inclusion of rice in burials of only one site, differences in mortuary wealth and apparent differential involvement in trade of exotic goods.

The small-scale differences in diet between sites documented here add to the growing body of evidence in Thailand for an unusual pathway to neolithisation, involving the persistence of mixed economies (King, 2008; White, 2011), and matrilocal systems of social organization (Bentley et al., 2005). The lack of uniformity in subsistence strategy also adds weight to the arguments made by White (1995; 2011) and O'Reilly (2003), for a decentralization of power and focus on household production, rather than large-scale control by elites, which might be expected to result in more uniform diet across a landscape.

The gradual uptake of agriculture proposed for SE Asia contrasts sharply with the complete and universal shift in subsistence strategy that characterizes the European Neolithic (e.g. Rowley-Conwy, 2011). There, despite new evidence for differential land access (Bentley et al. 2012; Bogaard et al., 2011), carbon and nitrogen isotope studies show that dietary uniformity is the norm and differences between sites are not present until the Bronze Age (e.g. Dürrwächter et al., 2006; Tafuri et al., 2009).

Conclusions

Archaeological evidence relating to material culture has already suggested high levels of cultural diversity in prehistoric Thailand. The evidence presented here reveals that this pattern extends to diet and subsistence strategy, contrasting sharply with the European Neolithic, where agriculture, and the cultural suit which accompanies it, appears to have been taken up uniformly across vast regions. In the Upper Mun River Valley isotopic results indicate that, from the Neolithic, culturally-mediated choices led to significantly different diet and material culture at sites within a ten kilometre radius. This evidence for cultural pluralism appears long before the advent of state society, as differences between groups arose over many generations.

Acknowledgements

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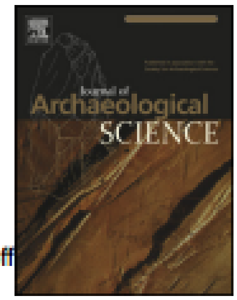
16. Manscript Three

Accepted Manuscript



Moving peoples, changing diets: Isotopic differences highlight migration and subsistence changes in the Upper Mun River Valley, Thailand

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Moving peoples, changing diets: Isotopic differences highlight migration and subsistence changes in the Upper Mun River Valley, Thailand.

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Abstract

The dramatic growth of dietary isotope studies in archaeological literature attests to the significant potential this technique has for shedding light on past societies. Human diet reflects complex, inter-linked factors such as status, cultural preferences or environmental constraints on food production. In this study dietary isotope analysis is used to examine the human skeletal remains from Ban Non Wat, northeast Thailand. The study aims to use isotopic data to give insight into patterns of migration and subsistence strategy during prehistory. Ban Non Wat is the most comprehensively excavated site in the Upper Mun River Valley (UMRV), and understanding of prehistoric society in this area is crucial to answering questions of how social complexity arose in the region. Carbon isotope analysis has highlighted migrant individuals invisible to strontium isotope analysis and shown links between unusual burial practice and differences in diet. Results also indicate that diet

changed substantially through time, with more reliance on rice in the Bronze Age, correlated with an increase in social differentiation. There is a move away from reliance on rice agriculture in the Iron Age, a time when oxygen isotopes show that environmental conditions were becoming drier, possibly resulting in rice agriculture becoming less viable.

Introduction

The study of diet in archaeological contexts not only gives information about past eating habits but is also linked to complex ideas about status, cultural taboos and preferences and subsistence strategy. In any society some foods are considered 'prestigious' and others 'poor' (e.g. van der Veen, 2003; Jelliffe, 1967). Diet also tends to vary regionally, thus differences in dietary isotope signals can be used to identify possible migrants (e.g. Schroeder et al., 2009). If long-term dietary trends are studied they have the potential to highlight changes to subsistence strategy or cultural preferences for different foods (Smith, 2006; Harris, 1987). Knowledge of diet can therefore add a great deal to our overall understanding of interaction, migration, subsistence and status, within and between archaeological sites.

The study of prehistoric diet through isotopic analysis is perhaps best known in the Americas, where carbon isotopes record a transition to C_4 maize agriculture (e.g. Schoeninger, 2009) or Europe, where carbon and nitrogen isotope signatures document an abrupt shift from a fishing and gathering diet to terrestrial-based diet of C_3 crops and domesticated animals (e.g. Richards et al., 2003). This study focuses on Southeast Asia, a less researched, and possibly more heterogeneous prehistoric region. It uses dietary isotopes in human mortuary remains from the Upper Mun River Valley (UMRV) of northeast Thailand.

The UMRV has long been of interest to archaeologists due to its abundance of both prehistoric and Angkorian period sites (e.g. Higham & Kijngam, 2009; Higham & Thosarat, 2005; Higham et al., 2007; White, 1995; O'Reilly, 2008). Many sites in this valley have been excavated, the most comprehensively being Ban Non Wat (Higham & Kijngam, 2009), marked on figure 1.

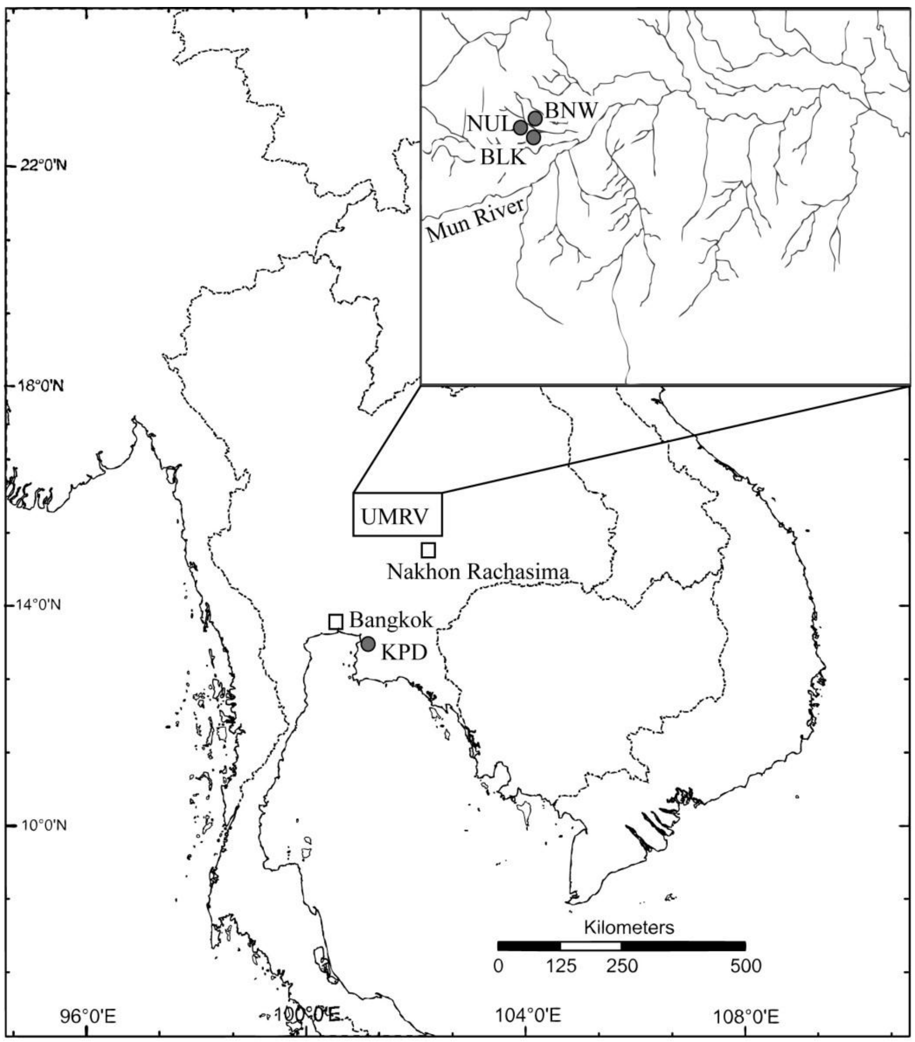

Figure 1: The geographic location of Ban Non Wat and other sites of the UMRV.

The excavation of Ban Non Wat has revealed burials from the Neolithic (1750BC) through to 400AD (Iron Age) (Higham & Higham, 2009). Differences in the number and type of mortuary goods show social stratification from the Bronze Age onwards (Higham, 2009; 2011), and geomorphological analyses indicate that moats were constructed from 200BC (McGrath & Boyd, 2001), most likely for the purposes of water control (Boyd, 2008). It is assumed that rice agriculture was practiced from first occupation of the site (Higham & Kijngam, 2011), though the extent to which this staple crop was relied upon is unknown.

Here dietary isotopes in human dental enamel are studied to answer a number of archaeological questions relating to migration, social groupings and subsistence change at Ban Non Wat:

Question 1: Does subsistence strategy change over time, particularly with climate change at the beginning of the Iron Age?

The occupation of Ban Non Wat covers approximately 1600 years, during which geomorphological and palynological studies indicate that there was a gradual trend towards drier conditions (Boyd & McGrath, 2001; Boyd et al., 1999; Boyd, 2008). Reduced rainfall led to the construction of moats in the Iron Age, and eventual abandonment of some sites in the area c.1400AD (Boyd, 2008). This building of moats to direct water flow, indicates that energy was expended to maintain the conditions required for rice agriculture, but it seems likely that subsistence strategy had to be changed in order to cope with environmental stress (e.g. Rosen, 1995; Orlove, 2005; Haberle & Chepstow-Lusty, 2000). It is also likely that game was driven from the area into the retreating forests, as archaeozoological evidence from nearby Noen U-Loke indicates a decrease in frequency of wild species in the later stages of site occupation (Higham et al., 2007).

In order to correlate dietary changes with climatic variation this study looks at oxygen isotopes in conjunction with carbon isotope analysis. Dansgaard (1964) showed that in the tropics there is an inverse relationship between the amount of rainfall and $\delta^{18}O$. Therefore we expect an increase in $\delta^{18}O$ at the onset of low rainfall conditions, and hypothesise that this may link to changes seen in the carbon isotope ratios of individuals.

The mortuary record of Ban Non Wat shows an increase in social stratification and the presence of an extremely wealthy elite during the second Bronze Age phase (Higham & Kijngam, 2009). While this elite may not persist beyond this phase (Higham & Kijngam, 2011), it is clear from mortuary wealth discrepancies that social inequality continues through the Bronze Age. An increase in social inequality and stratification is often linked to the ability to produce an agricultural surplus, and an increase in consumption of a staple crop (e.g. Renfrew, 1974; Sheratt, 1973). It is therefore hypothesised that the emergence of a social elite will correspond with a period of intensification of rice agriculture and consumption, resulting in more negative $\delta^{13}C$ ratios in Bronze Age individuals.

It is our **overall hypothesis** that we will see a transition to more negative values in $\delta^{13}C$ as rice agriculture is intensified, and that more positive $\delta^{18}O$ values will correlate with changes in diet, as changes in rainfall levels may link to difficulty maintaining rice agriculture.

Question 2: Whom do the Neolithic flexed burials represent?

At Ban Non Wat there are three Neolithic phases, one where burials were flexed, and two characterized by supine burials. The flexed burials appearto overlap temporally with the supine phases (Higham & Higham, 2009). It has been suggested by Higham & Kijngam (2011) that the Neolithic flexed phase at the site represents hunter-gatherers who lived alongside rice agriculturalists (the supine individuals). Higham supports this theory using various examples of flexed burials in hunter-gatherer contexts elsewhere in Southeast Asia (Higham & Thosarat, 1998; Shoocondej, 1994), and slight differences in material culture between the flexed and supine burials (Higham & Kijngam, 2011). Harris (2012), however, suggests that these individuals may be alternatively viewed as rice agriculturalists set apart from the rest of the population for unknown reasons, perhaps to do with status.

If the flexed burials do represent hunter-gatherers, then dietary isotopes should differentiate them from agriculturalists. The hunter-gatherer diet is likely to have been broad spectrum, including both meat and wild C_3 plants. Krigbaum (2003) showed that the $\delta^{13}C$ signature of hunter-gatherers can vary substantially depending on the amount of meat, fish and open forest plants consumed. If closed-forest foraging is the norm this yields $\delta^{13}C$ of approximately -14‰. If, on the other hand more meat, fish and open forest plants are used the $\delta^{13}C$ shifts to a less negative value, -12‰ and lower. Rice agriculturalists, with their greater reliance on a single C_3 plant have been shown by previous isotopic studies to have $\delta^{13}C$ values around -13‰ (Krigbaum, 2003; Bentley et al., 2005; 2009; Cox et al., 2011).

It is possible that hunter-gatherers using closed forest resources may have similar $\delta^{13}C$ ratios to rice agriculturalists, but palynological research indicates that heavy forestation close to Ban Non Wat is unlikely during the Neolithic (Boyd & McGrath, 2001). Any hunter-gatherers in the area are therefore likely to have exploited open forest/savannah environments within the river valley, giving them less negative $\delta^{13}C$ values than rice agriculturalists.

Question 3: Are there sex-based differences in diet present relating to social inequality?

Differences in mortuary wealth at Ban Non Wat show that there is social inequality present by the early Bronze Age (Higham & Kijngam, 2009). Inequality can be based on many factors including sex, kinship-group and personal merit. In other regions carbon isotope analysis has shown there to be dietary differences between males and females relating to social status (e.g. Ambrose et al., 2003; Jørkov et al., 2010).

In Thailand, sites such as Khok Phanom Di (Higham & Thosarat, 1994; Bentley et al., 2007) and Ban Lum Khao (Bentley et al., 2009b) have shown that female individuals are often amongst the wealthiest, or have important links with material culture traditions which the males lack. At Ban Non Wat, however, discrepancies in mortuary wealth seem to be unrelated to sex (Higham & Kijngam, 2011). We hypothesise that this lack of sex-based differentiation in mortuary wealth should be echoed in homogeneity of diet between males and females of each phase. If this is not the case it could indicate that sex did have an impact on status.

Question 4: Are unusual burials indicative of differences in origin or status?

At Ban Non Wat, with the exception of the flexed Neolithic individuals, most burials conform to the norm of being supine and oriented roughly N-S or E-W, depending on the mortuary phase. There are, however, two adult jar burials present in Neolithic phaseone.

These are very unusual as adult jar burial is not generally practiced in the region prior to the Iron Age, though infant jar burial is common and the norm at Ban Non Wat (Higham, 2011; Higham & Kijngam, 2009; 2011). Adult jar burial requires more energy to be expended on mortuary ritual (e.g. creation of a ceramic vessel which is large enough to contain an adult, digging of a far deeper grave pit than is necessary for a supine burial). Why then were these individuals singled out for such special treatment? Harris (2012) in his study of mortuary ritual at Ban Non Wat suggests that these individuals may be migrants to the site. Sr isotope ratios obtained from one of the jar burials (B28) do, in fact, indicate origins elsewhere (King et al., *in review*), and Higham & Kijngam (2011) note that B292, the other jar burial, is associated with cowrie shell mortuary offerings, perhaps indicating links with the coast. It is possible that this individual is also a migrant, but has not been identified in Sr isotope analysis due to the homogeneity of the geology across much of Thailand (King et al., *in review).*

Where strontium isotope analysis is limited by homogeneous geology it may be possible to identify individuals with different natal regions using childhood diet as a proxy. Even today different regions of Thailand have quite different dietary preferences (e.g. van Esterik, 1992) and in the past we have evidence for cultivation of millet in some regions and not others (Castillo, 2011; Weber et al., 2010). The consumption of millet, a C_4 crop, would cause a shift to less negative $\delta^{13}C$ in skeletal tissues (Hobbie & Werner, 2000). Similarly it is likely that coastal regions will have far greater input from marine resources into their diet, which also causes a positive shift in $\delta^{13}C$ value (Schoeninger et al., 1984). If jar burial is indicative of foreign origins then dietary isotope analysis may reveal this.

Materials and Methods

Archaeological samples

One hundred and eighteen adults from all 10 mortuary phases present at Ban Non Wat were analysed in the course of this study. The samples used in isotopic analysis were preferentially taken from the 2nd molar, as results from this tooth represent the diet/water source between 3-6years of age (Hillson, 1996). There is substantial within individual variation in isotopic ratio relating to differences in timing of tooth mineralisation/ rate of turnover in the skeleton. Isotopic results will therefore vary depending on which tooth or which element of the body is sampled (Balasse et al., 1999). This study only uses dental enamel, which mineralises during childhood and is unchanged throughout an individual's life.

Effort was taken to sample a roughly even number of males and females, and representative numbers from each of the mortuary phases i.e. the sample was weighted so more individuals were sampled from larger mortuary phases. The demographic make-up of the light stable isotope sample is given in table 1. Also analysed were five samples of domesticated pig enamel (*Sus scrofa*). These samples are from midden contexts and are not tied specifically to any one of the mortuary phases. It is assumed that pigs were kept in close proximity to the settlement in prehistory (as is the case in traditional ethnographically observed Southeast Asian societies e.g. Griffin, 1998), and that their diet will be similar to that of humans, making them likely to closely reflect the isotopic composition we would expect of local humans (Price et al., 2002).

Phase	Male	Female	Unknown	Total
Neolithic Flexed	1	2	0	3
Neolithic 1	5	3	0	8
Neolithic 2	4	7	1	12
Bronze Age 1	1	1	0	2
Bronze Age 2	4	2	2	8
Bronze Age 3	9	9	2	20
Bronze Age 4	15	23	1	39
Bronze Age 5	2	3	2	7
Iron Age 1	4	8	3	15
Iron Age 2	1	1	2	4
Total	46	59	13	118

Table 1: The demography of the sample taken from each of the mortuary phases at Ban Non Wat. Age data is not included as this is irrelevant to isotopic studies.

Carbon and Oxygen Isotope Analysis

Carbon and oxygen isotope analysis of dental enamel is used in this study to give information on diet and water sourcing/availability during enamel mineralisation. $\delta^{13}C$ reflects broad diet, with carbon isotopes fractionated on the basis of photosynthetic pathways in plant resources consumed by either humans or the animals they feed off. Results can therefore differentiate between C_3 crops (e.g. rice), which give a more negative $\delta^{13}C$ ratio, and C_4 crop use (e.g. millet), which give a more positive ratio (Ehleringer & Cerling, 2002). Carbon isotope ratios also differ significantly between marine and terrestrial ecosystems and so can be used to identify marine input into the diet. Marine resource use, however, is not considered likely at BNW, since the UMRV is too far inland for these to have been available. Carbon isotope results are interpreted using baseline data from King (2008), which gives typical isotopic results for the modern and archaeological plant and animal resources in use in the UMRV (figure 2).

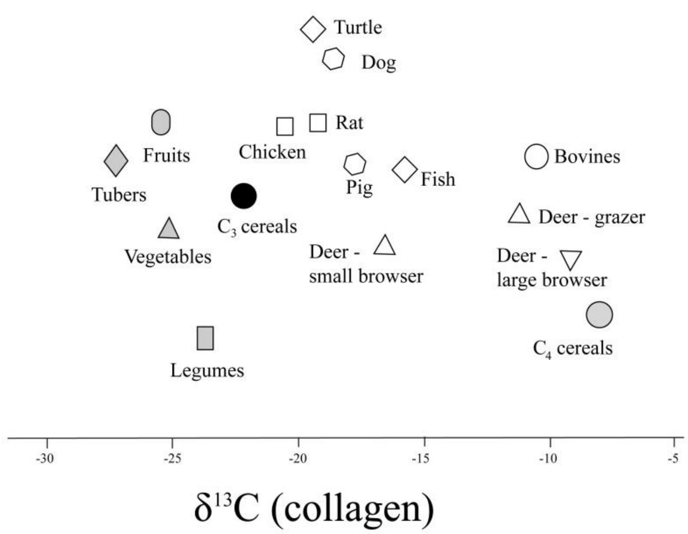

Figure 2: Baseline carbon isotope data from King (2008) for resources exploited in the UMRV. Note that $\delta^{13}C$ reported for animals is from collagen not enamel. In enamel $\delta^{13}C$ is higher by ~6‰, though this does depend on trophic level (Lee-Thorp et al., 1989).

Carbon isotopes enter the human skeletal system through resource consumption. They are then partitioned into the body's tissues through metabolic processes. Certain macronutrients are routed to specific body tissues, with the most significant of these processes being protein routed to collagen. Isotopic analysis of this collagen will give information on dietary protein intake, whilst dental enamel carbonate more reflects the whole diet (Jim et al., 2004).

Oxygen isotopes primarily reflect the water source used by an individual. They are fractionated on the basis of evaporation/condensation events, meaning the ratios found in water sources reflect geographic location, temperature and rainfall levels. The $\delta^{18}O$ of human dental enamel carbonate reflects the oxygen taken in through food and water consumption and respiration of atmospheric oxygen during childhood, when teeth are mineralising (Daux et al., 2008). This study focuses upon their use as a proxy for environmental change.

Isotopic ratios may be altered by post-depositional diagenesis. This is particularly true in monsoonal tropical areas, where seasonal inundation of burials and high levels of microbial activity can cause breakdown of skeletal elements and dissolution/recrystallisation events (King et al., 2011). Dental enamel carbonate was analysed in this study because it is less subject to diagenetic change and more likely to retain isotopic ratios *ad vivo* (Lee-Thorp & Sponheimer, 2003).

Oxygen and carbon isotopic ratios were measured in the Stable Isotope Laboratory, Department of Earth Sciences, Durham University. Diagenetic components were removed from 5-10mg enamel chips according to the method of Koch et al. (1997). Samples were then crushed using an agate pestle and mortar. Carbonate was released from enamel by reaction with phosphoric acid and CO_2 was separated using a GasBench II chromatograph.

Isotopic ratios were measured using a Thermo Electron MAT253and normalised to international standards NBS 19 and LSVEC. Repeated measurements of internal standard DCS01 were used to constrain temporal drift in measurement. Powdered samples were run in two periods of analysis, with the standard deviation of DCS01 measurements in each of these periods being 0.05‰ for $\delta^{13}C$ and 0.04‰ in each (2s.d.). The precision of analysis on teeth was established using repeat measurements of selected samples (B144 and B263), giving average error of 0.18‰.

Results of stable isotope analysis are plotted against strontium isotope ratios obtained from the same samples in a concurrent study (King et al., *in review*).

Results

Figure 3 shows results of carbon isotope analysis, plotted against strontium isotope ratios obtained from the same samples in a concurrent study.

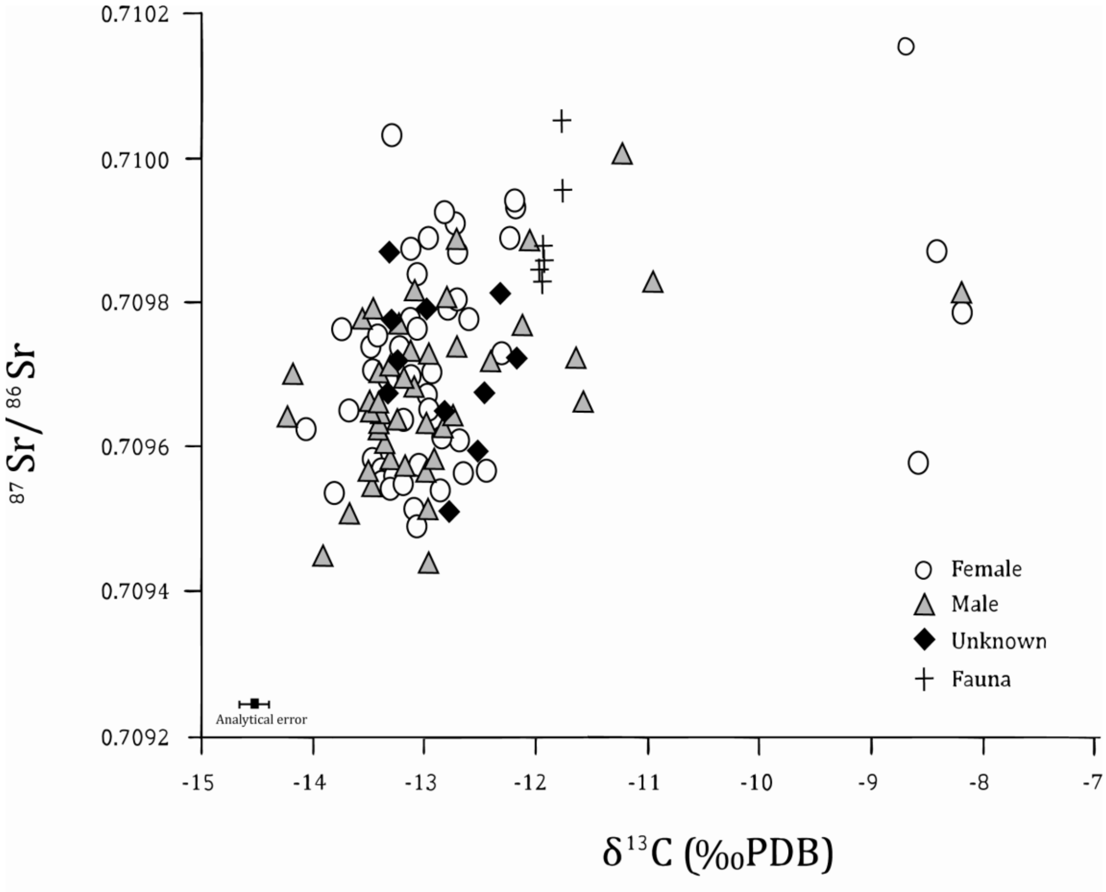

Figure 3: Carbon isotope results plotted against Strontium isotope results from Ban Non Wat.

The strontium isotope data is discussed elsewhere (King et al., *in review*), so the focus of this study is the light isotope results. These results highlight the presence of five clear outliers falling at around -8‰, four females and one male.When these data are considered as a whole there is no significant difference between males and females in $\delta^{13}C$ mean (p = 0.585, two tailed t-test). Mean data for males and females in each of the mortuary phases in table 2.

Phase	Mean Males		Mean Females		Overall mean	
	$\delta^{13}C$ (‰ PDB)	**$\delta^{18}O$ (‰ SMOW)**	**$\delta^{13}C$ (‰ PDB)**	**$\delta^{18}O$ (‰ SMOW)**	**$\delta^{13}C$ (‰ PDB)**	**$\delta^{18}O$ (‰ SMOW)**
Neo Flex (2)	N/A	N/A	N/A	N/A	-12.1	24.9
Neo 1 (2)	-12.5	26.5	-12.2	26.8	-12.4	26.5
Neo 2	-12.7	25.4	-12.9	26.5	-12.8	26.2
BA 1	-12.1	26.3	-12.7	26.6	-12.4	26.5
BA2	-13.5	26.5	-13.4	26.5	-13.4	26.5
BA3	-13.5	26.6	-13.3	26.6	-13.3	26.6
BA4	-13.2	26.7	-13.2	26.8	-13.2	26.8
BA5	-12.9	27.0	-12.7	26.5	-12.9	26.9
IA1(1)	-12.0	27.3	-12.9	26.6	-12.6	26.9
IA2	N/A	N/A	N/A	N/A	-12.8	27.6

Table 2: Mean isotope results given by mortuary phase and sex. N/A indicates not enough individuals were assigned a sex in the mortuary phase to calculate mean results. These means are for the local range with outliers excluded. Numbers in parentheses after the phase indicate the number of outliers in each phase. Neo = Neolithic, BA = Bronze Age, IA = Iron Age.

Figure 4 plots carbon isotope values according to mortuary phase to test for dietary differences through time, with outliers excluded in order to focus on local individuals. The results indicate an abrupt change to more negative $\delta^{13}C$ values between the first and second Bronze Age phases, and a gradual increase in $\delta^{13}C$ through the Iron Age. MANOVA shows both of these changes to be statistically significant (p = 0.0001 Tukey's test). Two-tailed *t*-tests between the phases show that the phase means are significantly different (p=0.002), but the variance around the means is not. ANOVA analyses looking at differences in mean and variance between males and females in each of the mortuary phases show significant differences in the mean isotopic values between the sexes in the second and third Bronze Age phases ($p < 0.05$) only.

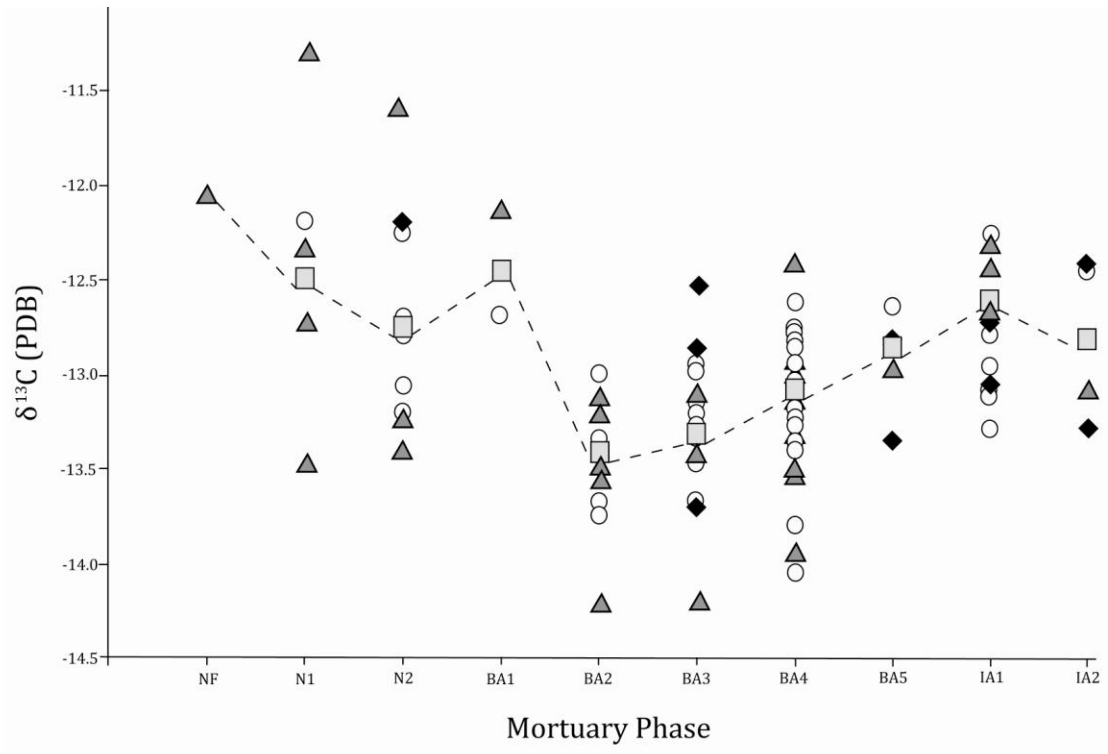

Figure 4: Carbon isotope results plotted against mortuary phase with reference to biological sex.Symbols used for the sexes are the same as those in figure 2. Mortuary phase contractions are as follows: Neo = Neolithic, F = flexed, BA = Bronze Age, IA = Iron Age. Dotted line joins the average values in each phase.

Figure 5 shows changes in oxygen isotope ratios over time, and indicates a general trend to higher $\delta^{18}O$ since the Neolithic.

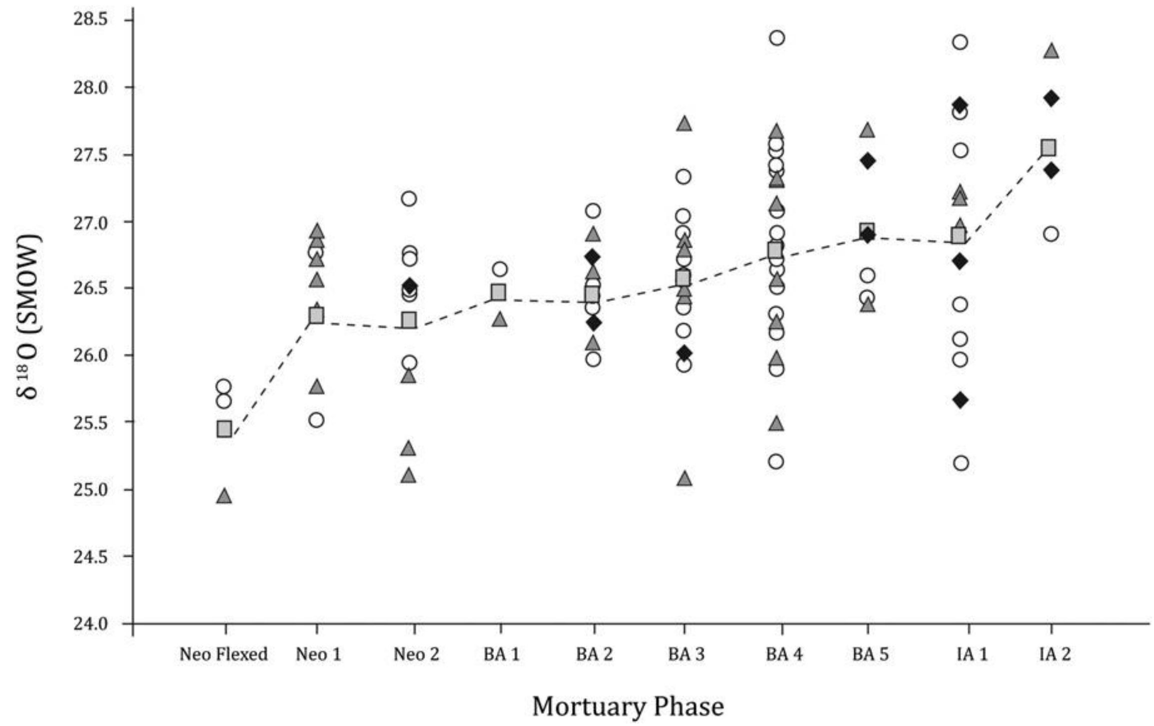

Figure 5: δ^{18}O values plotted against mortuary phase, with reference to biological sex. Symbols and contractions used are the same as those in figure 3. Dotted line joins the average values in each phase, highlighting the trend towards higher δ^{18}O values over time.

Discussion

Are there changes to subsistence strategy over time?

The overall pattern in δ^{13}C results over time can be used to give information on subsistence practice changes. The main patterns seen in this dataset are that δ^{13}C values become more negative between the first and second Bronze Age phases, and from the late Bronze Age into the Iron Age there is a gradual increase in δ^{13}C values.

Taken alone these patterns in the isotopic results could be interpreted as being due to sampling bias, though this is considered unlikely due to the large samples analysed, particularly in the Bronze Age phases. When considered with other archaeological lines of evidence, however, these isotopic results add to the big picture of social change emerging from research in Southeast Asia in general and Northeast Thailand in particular.

A change to more negative average $\delta^{13}C$ values in the Bronze Age could be interpreted as indicating a move away from a broad spectrum diet towards a greater reliance on C_3 crops such as rice. This is supported by the theory put forward by Boyd and Chang (2010), which suggests that the initial colonists of Ban Non Wat, despite being rice agriculturalists, did not focus their subsistence strategy on or place great importance on this crop. It also fits with the hypothesis that increased reliance on rice agriculture, and the creation of a surplus would coincide with social stratification (Higham & Kijngam, 2009).

The less negative results $\delta^{13}C$ ratios of the Iron Age individuals may indicate a second change in subsistence strategy, with less negative carbon isotope ratios linked to a move away from reliance on rice agriculture and towards supplementation of the diet with meat or C_4 crops. Geomorphological evidence from the Iron Age indicates that this period was characterised by moat building in order to control water resources (McGrath & Boyd, 2001), a decrease in forest plant species, and a move towards savannah environment (Boyd & McGrath, 2001). Oxygen isotope data from this study and others using oxygen isotope ratios in stalagmites (Maher, 2008; Wang et al., 2005), and foraminifera (Lückge et al., 2001) echo the idea of environmental change. They show a weakening of the monsoon and increase in dry conditions throughout Ban Non Wat's occupation. Use of oxygen isotopes as a climatic indicator is further justified through regressing modern precipitation data onto the archaeological carbonate $\delta^{18}O$ values of this study (values converted to $\delta^{18}O_p$ using Chenery et al. (2012) and regressed using Daux et al. (2008), equation 6. This shows a compression of roughly 2‰ between calculated values of water sourced in prehistory, and modern precipitation, indicating a trend towards drier conditions. It is hypothesised that these changes in climate would have led to rice agriculture becoming less sustainable due to its reliance on wetland conditions.

The correlation between oxygen isotope results and carbon isotope shifts found by this study is unlikely to be a coincidence and is interpreted as real subsistence change due to climatic deterioration. The nature of this subsistence change is debateable; both increased reliance on animal husbandry/hunting and use of C_4 crops such as millet could cause the shift. There is, as yet, no phytolith evidence for the presence of millet in the UMRV (Castillo, 2011), thus the animal husbandry hypothesis seems more likely, though further archaeobotanical investigation in the area could change this.

The results of this study are not alone in suggesting subsistence change over time in northeast Thailand. The trends reported here are echoed by the work of King (King & Norr, 2006) at Ban Chiang. At this site it is suggested that the shift in $\delta^{13}C$ is due to increasing use of C_4 crops later in the site's occupation. Boyd & Chang (2010) also suggest that rice agriculture became more difficult in the Iron Age, which increased its ritual importance, leading to the rice burials seen at nearby Noen U-Loke (Higham et al., 2007).

Are hunter-gatherers present at Ban Non Wat?

It is notable that almost half the individuals analysed in the flexed Neolithic phase are isotopic outliers, either in terms of carbon or strontium isotopes, which are reported elsewhere (King et al., *in review*). The carbon outliers of this phase have less negative $\delta^{13}C$

than others in the site, indicating less reliance on C_3 crops such as rice, andmore input from meat or C_4 crop food sources. This is the kind of signature expected from more broad-spectrum hunter-gatherers, supporting Higham & Kijngam's (2009) interpretationof this phase. Pietrusewsky & Douglas (2002; Douglas & Pietrusewsky, 2007) similarly argue for broad spectrum hunter-gatherers in the early phases of Ban Chiang based on osteological evidence, with a varied dietpersisting into the metal-ages at this site. Isotopic analysis has supported this conclusion (King & Norr, 2006).

An alternative explanation for this pattern may be that the isotopic outliers in the Neolithic phases at Ban Non Wat are immigrants. If their less negative $\delta^{13}C$ values are not indicative of meat input through broad spectrum hunting, but of C_4 resource use, then they are likely to have had their origins elsewhere. There is no archaeological evidence for C_4 agriculture in the area (Castillo, 2011). Millet is, however, likely to have been grown in neighbouring valleys (Weber et al., 2010; Castillo, 2011).

If outlying $\delta^{13}C$ values indicate migration then a substantial proportion of the Neolithic flexed phase are immigrants. This should not be surprising as the Neolithic flexed burials represent the earliest occupation of the site, and it stands to reason that the first settlers of BNW came from elsewhere. The supine mortuary phases at the site contain proportionally very few isotopic outliers. This suggests that migration, after site establishment, was minimal and unlikely to have been a significant process in terms of social development.

Higham & Kijngam (2011) report that the Neolithic flexed burials are associated with very different mortuary assemblages to the supine Neolithic burials. This may be due to a difference in lifestyle, but it is also possible that the differences in mortuary assemblages are related to migrant origins. For instance burial B461 is one of the carbon outliers ($\delta^{13}C$ = -8.41), and is also associated with crudely fashioned shell beads of the marine *Anadara sp.*, a genus not found in any other burial at BNW. This may indicate that B461's origins are coastal, and their unusual $\delta^{13}C$ ratio evidence for marine resource use in childhood.

Are there differences between the sexes in terms of diet at Ban Non Wat?

There are significant differences in mean carbon isotope ratios between the sexes in the Neolithic flexed, Bronze Age 2 and 3 phases at Ban Non Wat. The second Bronze Age phase is also the only phase in which we find 'super-burials', evidence for an extremely wealthy elite (Higham & Kijngam, 2011), though mortuary wealth differences in this phase do not appear to be based on biological sex (Higham & Kijngam, 2009). It is interesting then that there *are* significant differences between males and females in terms of dietary isotope ratios at this time. This may indicate that, despite there being no notable difference in mortuary wealth between males and females, biological sex did have some impact on an individual's position in society. This correlates with King & Norr's (2006) work, which shows significant dietary differences between males and females in both the Bronze and Iron Ages at Ban Chiang, periods in which social differentiation was occurring (King & Norr, 2006).

Do we find correlations between unusual mortuary practice and diet?

The only two adult jar burials (B292 and B28) found at the site are both isotopic outliers, B28 in $^{87}Sr/^{86}Sr$ (King et al., *in review*), and B292 in $\delta^{13}C$. Their unusual burial could be indicative of foreign origins, with these individuals not conforming to local mortuary traditions, but instead retaining those of their natal societies. There is no known evidence for adult jar burial being practiced elsewhere in Thailand at this time, so if this hypothesis is correct it may mean that these are long-distance immigrants. Infant jar burial, on the other hand, is present in Ban Non Wat and the surrounding sites, so an alternative hypothesis is that the individuals were accorded a different status due to their non-local origins.

Conclusion

The analysis of dietary isotopes from the cemetery sample of Ban Non Wat has given new information about subsistence strategy and society during prehistory. We find evidence for an increase in C_3 crop use, coinciding with increased social stratification in the Bronze Age, then a lessening of reliance on C_3 food sources in the Iron Age, correlating with the onset of drier environmental conditions. Through the study of isotopic results with reference to biological sex and mortuary practice, significant differences between males and females in the mortuary phases associated with the highest discrepancy between 'rich' and 'poor' individuals are revealed. There is also evidence for individuals with unusual mortuary practice, e.g. jar burials or flexed Neolithic burials, having different diets in childhood, making them possible immigrants to the site.

Acknowledgements

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17.Manuscript Four

Isotopes and Osteology: Using the multi-disciplinary approach to establish population affinity at Ban Non Wat, Thailand.

Charlotte L. King, Nancy Tayles, Helgi P.Gunnarsson,Una Strand Viðarsdóttir

Abstract

Isotopic studies in the Upper Mun River Valley of Northeast Thailand have revealed little long-distance migration. Short-distance migration seems likely, but is difficult to identify isotopically due to the homogeneity of underlying geology in the region. In this study we evaluate whether or not osteological evidence, such as cranial morphology or dental non-metric trait recording, may be of use in identifying external origins. These techniques are applied to the cemetery sample of Ban Non Wat to reveal correlations between cranial shape and unusual mortuary practice and non-metric trait frequency. Osteological data is used to test the hypothesis that the Neolithic flexed burials at the site represent a distinct population of hunter-gatherers and find little evidence for this mortuary phase being morphologically or genetically distinct from the supine burials. Osteological indicators of kinship are also compared to carbon isotope results in an effort to examine whether family groups cluster in terms of diet, but no correlations were found.

Introduction

Ban Non Wat is one of the best-known sites in the rich archaeological landscape of the Upper Mun River Valley (UMRV), Northeast Thailand (figure 1). This area was initially occupied in the Neolithic (c. 1750BC), and saw a rise in social complexity through the

Bronze and Iron Ages, culminating in state society when the region was annexed by the Angkorian empire in 1100AD (Higham, 2002; Higham & Kijngam, 2009). Debates regarding the nature of a rise in social complexity and the impact of migrant peoples, however, are still prevalent in this area.

While isotopic research has shown a lack of long-distance migrants into the UMRV in prehistory (Bentley et al., 2009b; Cox et al., 2011; King et al., *in review*), the level of short-distance migration, marriage exchange and interaction across the archaeological landscape is still relatively unknown. The most contentious issue in the area, however, is the nature of social organisation.

The presence of extremely wealthy individuals in the second Bronze Age phase has been interpreted as the emergence of an elite and rank-based hierarchy by researchers such as Higham& Kijngam (2009; 2012). Others, however, argue that a continuum in mortuary wealth, and evidence for household-based centres of production (White, 1995; O'Reilly, 2003) link more to the concept of heterarchical organisation (Crumley, 1995). There is a need for more evidence regarding kinship structures and status assignation before this debate can be laid to rest.

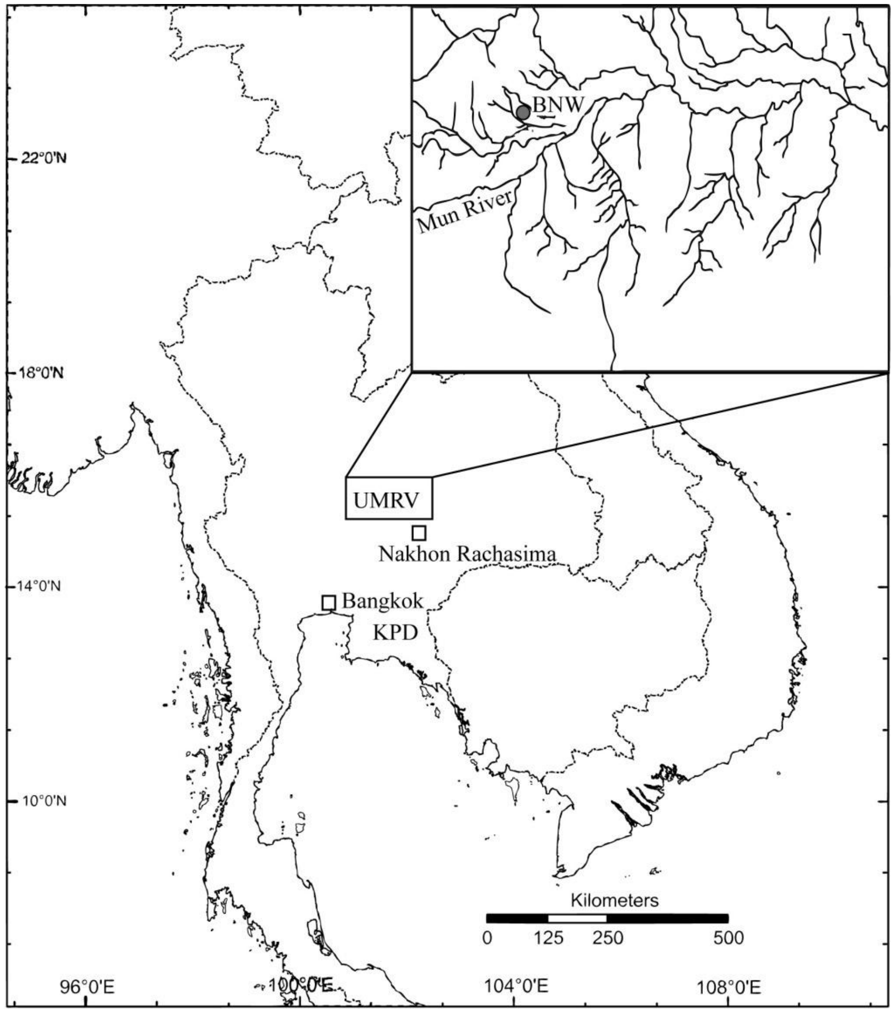


Figure 1: The location of the Upper Mun River Valley and Ban Non Wat.

In an attempt to address the fundamental question of how social complexity arose in this area, we have previously undertaken an intensive isotopic study using the cemetery sample of Ban Non Wat (King et al., *in press;* King et al., 2013). In recent years strontium isotope analysis has been the method of choice for the resolution of debates relating to migration and population affinity (Bentley, 2006; Montgomery, 2010). This method, however, can only highlight migrants if they come from geologically distinct areas, which causes difficulties when the surrounding geology is relatively homogeneous, as in the Upper Mun River Valley (figure 2).

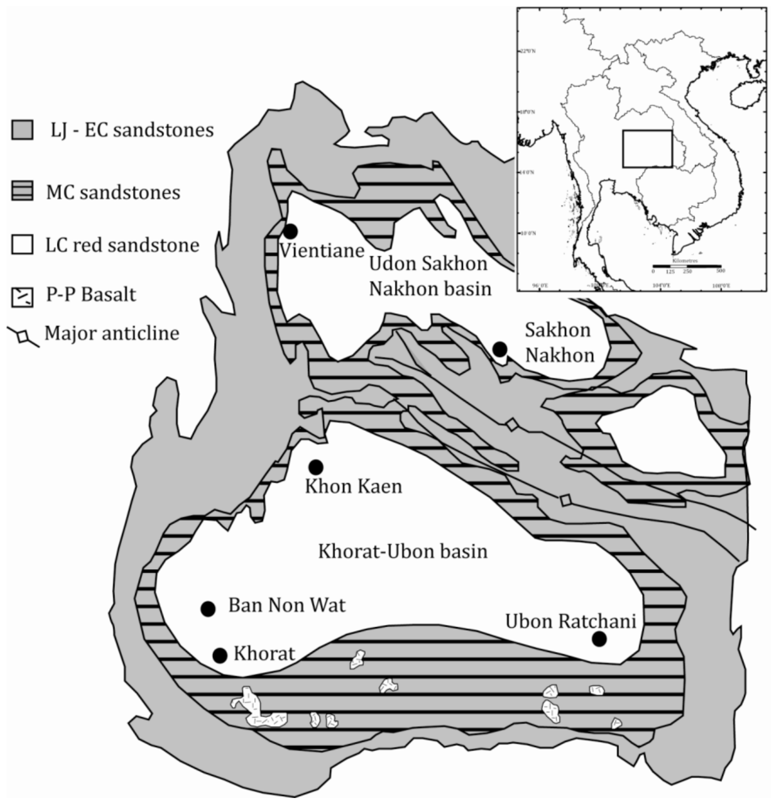


Figure 2: Showing the broad-scale underlying geology in the UMRV and surrounding valleys. Note the prevalence of sandstones, formations which are likely to be isotopically indistinguishable from one another (after Charusiri et al., 2006)

Since the 'morphometric revolution' (Rohlf and Marcus, 1993), however, geometric morphometric techniques have been increasingly used as a tool in quantifying and tracing human (and animal) diversity and origins. In particular the study of cranial shapehas been used to analyse population affinities and trace human migrations (von Cramen Taubadel & Pinhasi, 2011; Leach et al., 2010; Ousley et al., 2009; Buck & Strand Viðarsdóttir, 2012).

The morphology of the cranium is related to both genetic and epigenetic factors. Strand Viðarsdóttir et al. (2002), for instance, described the plasticity of facial growth in humans, and Roseman& Weaver (2004) have used craniometric in combination with geographic and climatic data to show that measurements on the face (particularly the nasal and zygomatic heights) are closely related to climatic variation. Regardless of whether cranial differences are due to underlying genetics or plastic response to the environment, if found in individuals of the same cemetery they are likely to indicate that some individuals have non-local origins, as the likelihood of local individuals experiencing a different environment to their contemporaries is unrealistic.

Geometric morphometric techniques differ from traditional craniometric techniques in that shapes are considered as configurations of landmarks, not reduced to a series of disconnected linear distances. This means that the geometry of the shape can be more accurately studied, and referred back to at all stages of statistical analysis. Geometric morphometric analysis also partitions form into size and shape components, meaning that the effects of size on variation in shape (allometry) can be quantified and removed (Bookstein, 1989), if so desired, prior to analysis. It is therefore preferable to use geometric morphometric techniques over traditional cranial measurements, and there is an increasing movement towards using these techniques to address archaeological problems.

The potential these techniques have for shedding light on past population movements has been highlighted by a recent study by Martínez-Abadías and colleagues (2006). This research indicated that not only could colonial long-distance migrants be identified within a cemetery sample, but also their offspring, as their cranial shape reflected admixture with the local populace. Ross et al. (2004) have applied geometric morphometricsto the study of population history in Cuba, a context where traditional craniometric and non-metric techniques had been unable to successfully differentiate populations. In this context morphometric techniques were able to differentiate the different populations present and have contributed to forensic identifications.

In Southeast Asia traditional craniometric techniques have been widely used to analyse population history. This is exemplified by Hanihara's (2006) work, which highlights the biological affinities of early Southeast Asians and the differences between ancient and modern populations. Pietrusewsky's (1988; 1997; 2006) work comparing craniometric data from prehistoric Asian populations has also highlighted real biological differences between inland and coastal populations in the Southeast Asian peninsula.

Work by Matsumura (2008) at Man Bac, Vietnam, using traditional craniometric analyses has shown how useful cranial morphology can be in understanding population history. Here the close affinities of the Man Bac population to Dong Son Vietnamese and modern Chinese samples, as opposed to Hoabinhian or Neolithic Vietnamese samples highlighted the migrant origins of the population. Together these studies have shown that Southeast Asia was not a biologically homogenous whole during prehistory, and that the study of cranial morphology has the potential to add to understanding of prehistoric population affinities.

Non-metric dental and skeletal traits can also be used to differentiate different populations in archaeology. First used in the 1920s (e.g. Hrdlicka, 1920; Wissler, 1931)0, non-metric trait recording continues to be applied today to assess human population origins (e.g. Hanihara, 1992; Irish, 2006; Nikita et al., 2012). Modern studies of populations using non-metric traits usually use mean measure of divergence (MMD), or D^2 Mahalanobis distances (see Irish, 2010 for a review) to assess affinities. In order to apply these techniques, however, the researcher must have knowledge of the frequency of non-metric trait occurrence in all possible parent populations, to avoid misclassification.

In Southeast Asia non-metric techniques have been used to identify broad patterns of population affinity, but have not yet been used to look at inter-regional differences. Studies by Hanihara (1992), Pietrusewsky (1994), Pietrusewsky & Douglas (2002), and Turner (1992) have used dental non-metric traits to highlight continuity between the modern and ancient populations of Thailand, and long-standing admixture with Northern populations.

Matsumura & Hudson (2005) in one of the most comprehensive dental non-metric studies in Southeast Asia have shown differences in non-metric trait occurrence between different prehistoric sites. We know, therefore, that differences in non-metric trait frequency between archaeological sites do exist, and study of these traits may shed light on local/migrant origins within a site.

Research Questions

In this study we use these geometric morphometric and non-metric techniques in combination with already reported isotopic results (King et al., 2013; King et al., *in press*) to assess whether they can be effectively used toidentify migrants, and whether they could provide useful, cost-effective, non-invasive and non-destructive alternatives to isotopic analysis. Geometric morphometric methods and dental non metric trait recording are also applied to a number of archaeological questions specific to Ban Non Wat:

Do flexed Neolithic burials represent a genetically distinct hunter-gatherer population?

At Ban Non Wat there are three Neolithic phases, one with flexed burials, and two characterized by supine burials. Radiocarbon dating has shown that these flexed burials overlap temporally with both the first and second phases of supine Neolithic burials at the site (Higham & Higham, 2009). The flexed position of these burials has been linked by Higham & Kijngam (2011) to the burial practices of indigenous prehistoric hunter-gatherers (Higham & Thosarat, 1998; Shoocondej, 1994). Differences in mortuary assemblage between the flexed and supine burials (Higham & Higham, 2009; Higham & Kijngam, 2011), have compounded the idea that these people are truly different. These lines of evidence have led some workers to the interpretation that flexed burials represent a genetically separate group of hunter-gatherers living alongside the rice agriculturalists represented by the supine burials (Higham & Kijngam, 2011).

If this is the case and flexed burials represent an indigenous community, distinct from an intrusive agricultural population, there are likely to be differences in cranial morphology and non-metric trait frequencies between the groups. This hypothesis will be tested in the course of this study.

Is there any evidence that kinship/genetic relatedness had an impact on status?

There is evidence for social inequality from the Bronze Age onwards at Ban Non Wat (c. 1050BC). There are mortuary wealth discrepancies within a single mortuary phase, particularly apparent in the second Bronze Age phase, where richly decorated super-burials are juxtaposed with those almost without mortuary wealth (Higham & Kijngam 2009; 2011). Currently the prevailing interpretation of social differentiation is a hierarchical one (c.f. Higham & Kijngam; 2012). Hierarchical organisation is generally based on a hereditary ranking system (e.g. Peebles & Kus, 1977) in which status is transferred through family lines and kinship groups are of a broadly similar status.

Under strict hierarchical organisation there are also often links between diet, place of origin and status (van der Veen, 2003; Burmeister, 2000; Rouse, 1995). If organisation is a hierarchy, links between osteological indicators of kinship and isotopic results might be expected e.g. family groups sharing similar non-metric trait signatures will have the same status, and therefore may share a culturally proscribed diet.

Are individuals with evidence for unusual mortuary ritual osteologically different from the rest of the sample?

Some of the most interesting individuals in terms of mortuary practice found at Ban Non Wat are the two adult jar burials, B28 and B292 (figure 3). Adult jar burial is otherwise unknown in the region prior to the Iron Age. It has been suggested by Harris et al. (2012), that this unusual mortuary practice may relate to migrant origins, and this is supported by recent isotopic work (King et al., 2013). In order to further test this interpretation the cranial morphology of these individuals was compared to that of 'local' individuals, to assess whether their migration had occurred from genetically similar populations, and whether their migrant status could have been identified on the basis of morphology alone.

Figure 3 – Adult jar burial B28 (photo courtesy of Prof. Charles Higham)

Materials

Cranial morphology, dental non-metric traits and isotopic ratios were analysed in a cemetery sample from Ban Non Wat. 88 individuals had crania complete enough to allow geometric morphometric analysis. One hundred and thirty individuals, which included the 88 analysed using morphometric techniques, were recorded for dental non-metric traits, and all of these were analysed isotopically. Only individuals from Neolithic and Bronze Age mortuary phases were analysed using geometric morphometric techniques, as the Iron Age is not as well preserved and most crania are incomplete. The demography of the sample is given in table 1.

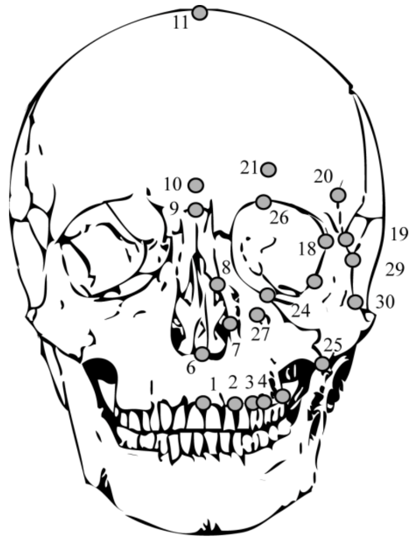
Mortuary Phase	**Male**	**Female**	**Unknown Sex**	**Total**
Neolithic Flexed	4	4	0	**8**
Neolithic 1	5	4	0	**9**
Neolithic 2	6	7	1	**14**
Bronze Age 1	1	1	0	**2**
Bronze Age 2	6	4	2	**12**
Bronze Age 3	11	9	3	**23**
Bronze Age 4	22	26	3	**51**
Bronze Age 5	5	4	2	**11**
Total:	61	59	7	**130**

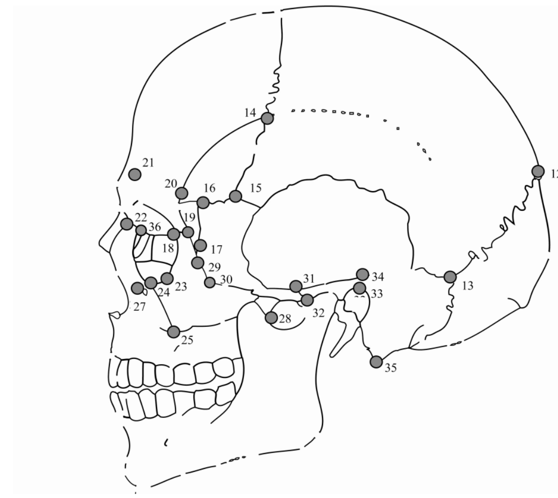
Table 1: Demography of the sample analysed during osteological and isotopic analysis.

Methods

Geometric morphometrics

A suite of 42 three-dimensional landmarks was recorded from the crania of Ban Non Wat using aMicroscribe MLX digitiser (Immersion Corporation; San Jose). Thelandmarks were selected to best describe the shape of the cranium, and based on published studies of human craniofacial variation using the same techniques (e.g. Buck and Strand-Viðarsdottir, 2012, Henessey and Stringer, 2002, Strand-Viðarsdottir, et al., 2002). Landmarks were collected unilaterally, with only the left lateral side of the vault recorded. These landmark points are shown in figure 4, and described anatomically in table 1 of the supplementary data.





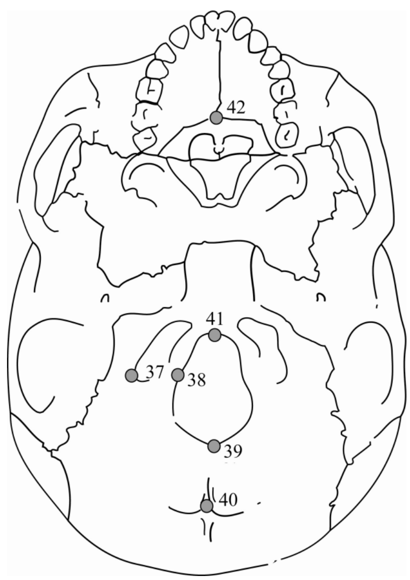


Figure 4: Anatomical landmarks digitised during geometric morphometric analysis.

Not all landmarks were present on every cranium, and only those which could be accurately placed were included in the analysis. Translational, rotational and scalar differences in samples were corrected for using generalized procrustes analysis (Bookstein, 1986; 1991), shape differences were visualised using principal components analysis and sexual dimorphism was corrected for by standardising each sample to the mean of their sex, then to the overall mean. All these operations were conducted using the EVAN toolbox (©Evan Society, 2012).

To statistically identify an individual as an outlier using geometric morphometric analysisthe data was first procrustes fitted, the mean shape of the sample calculated, and the Euclidian distance of each sample from the mean established. A chi-squared statistic was then calculated for each individual using *n* degrees of freedom (where *n* is the number of landmarks multiplied by the number of dimensions). Statistical significance was set as $p = 0.01$, to ensure conservative estimates of migrant status. A second iteration of this test was performed where the individual being looked at was not included in the mean (i.e. the assumption was made *a priori* that the individual was an outlier). This is a more relaxed mode of calculation and likely to maximise each individual's distance from the mean, and thus identify a greater number of possible migrants. This process was programmed and run in Matlab (The MathsWorks Inc., 2010).

Dental non-metric traits

The dental non-metric traits recorded are listed in table 2 and scored using the ASU recording system (Turner et al., 1991; Hillson, 1996). These traits were chosen as those most likely to be present within Southeast Asian populations, based on studies by Hanihara (1968) and Matsumura & Hudson (2005).

Dental Non-Metric Trait	Scoring System	Description
Shovelling (on UI_1 and UI_2)	0-5 based on ASU scale of severity.	Marginal ridges on the incisor becoming especially prominent, enclosing a deep fossa on the lingual surface.
Carabelli's cusp (UM_1)	0-7 based on ASU scale of severity.	Presence of an extra cusp arising from the base of the mesiolingual cusp in molars. Perhaps present as a cusp rivalling main cusps in size, or as a small ridge, pit or furrow.
Sixth/Seventh cusp (LM_1, LM_2)	Presence/absence	Presence of a sixth/seventh cusp on the lower molars, usually located on the distal aspect of the occlusal surface. In most cases the $6^{th}/7^{th}$ cusps are only about a quarter of the size of the other cusps.
Deflecting Wrinkle (LM_1)	0-5 based on angle at which ridge contacts the ectoconoid.	Wrinkle in the ridge of the metaconid curving distalward at the central part of the occlusal surface.
Peg-shaped teeth	Presence/absence	Distal lobe of the incisors is reduced,

(2nd incisors)		giving a peg shape
Supernumary Teeth	Presence/absence	Additional teeth, usually found lingual to the normal tooth row.
Enamel Extensions	Presence/absence	Enamel present as a line or lobe extending below the line of the cementum, usually directed apically towards the bifurcation of the roots. Also includes enamel pearls, small spherical masses of enamel, unconnected with the crown, usually located at the point of root bifurcation.

Table 2: Dental non-metric trait descriptions and the scoring systems used to record them.

Isotopic analysis

Isotopic analysis was conducted in a concurrent study, and the methods used and results are reported in detail elsewhere (King et al., 2013; King et al., *in press*). Isotopic data was collected from samples of dental enamel from the maxillary second molar of individuals. Strontium isotope data was obtained through MC-ICP-MS analysis at the Northern Centre for Isotopic and Elemental Tracing, Durham University. Carbon isotope analysis was conducted on dental enamel carbonate, and isotopic ratios measured using a Thermo Electron MAT253 mass spectrometer. These results are used here for comparative purposes, in order to assess whether the same individuals are identified as migrants by both isotopic and osteological/dental techniques.

Results

Figure 5 presents the results of geometric morphometric analysis with isotopic outliers (i.e. migrant individuals) highlighted.

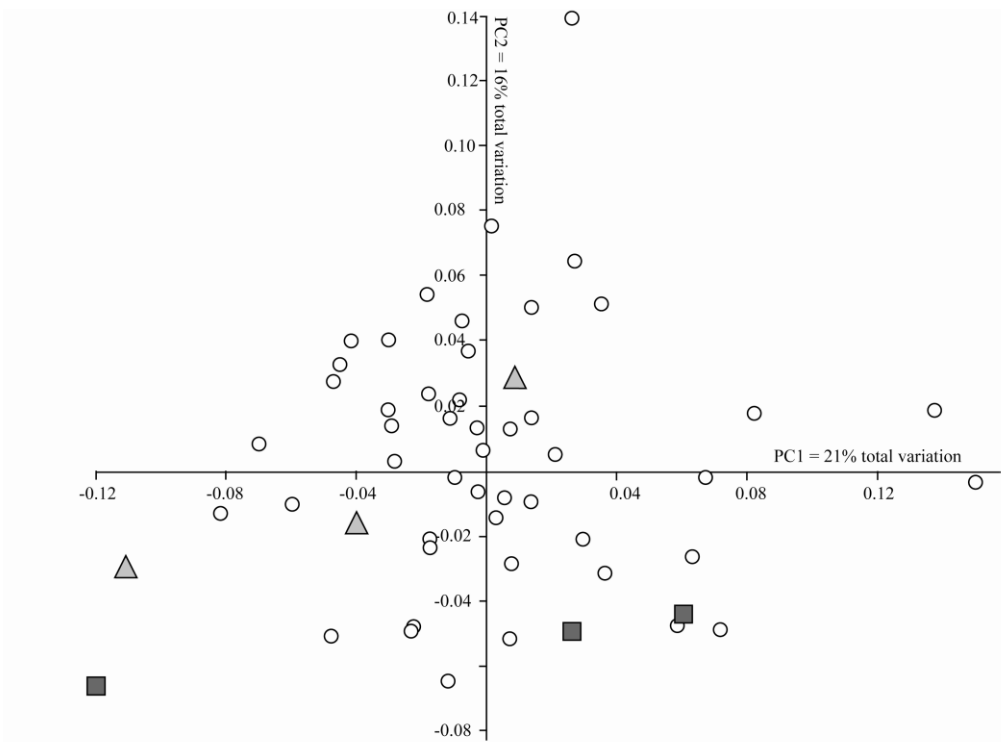


Figure 5: Principal components analysis based on morphological variation within the BNW sample (PC1 vs PC2). Isotopically 'local' individuals = white circles, carbon isotope outliers = dark grey squares, strontium isotope outliers = light grey triangles.

Carbon isotope outliers all have similar values on PC2, at the most negative extreme of the distribution (figure 5). Strontium isotope outliers fall well within local variation in morphology, even on higher components.

Isotopic results are plotted with non-metric trait prevalence in figures 6-8. Enamel extensions (figure 6) appear to be absent in individuals with more positive $\delta^{13}C$, but common within the local range for BNW. Carabelli's trait (figure 7) is uncommon, but present in both locals and immigrants. Sixth cusps (figure 8) do not cluster within the local range and are not present in the isotopic outliers. Non-metric traits which are not plotted in these figures were not prevalent enough for study in this population.

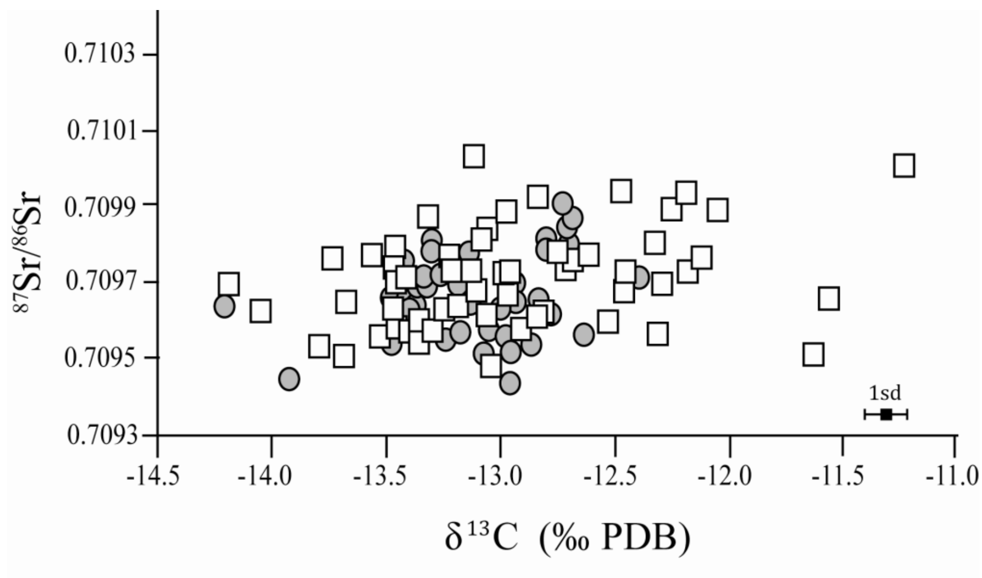


Figure 6: Isotopic results plotted with reference to enamel extension presence (grey circles) and absence (white squares)

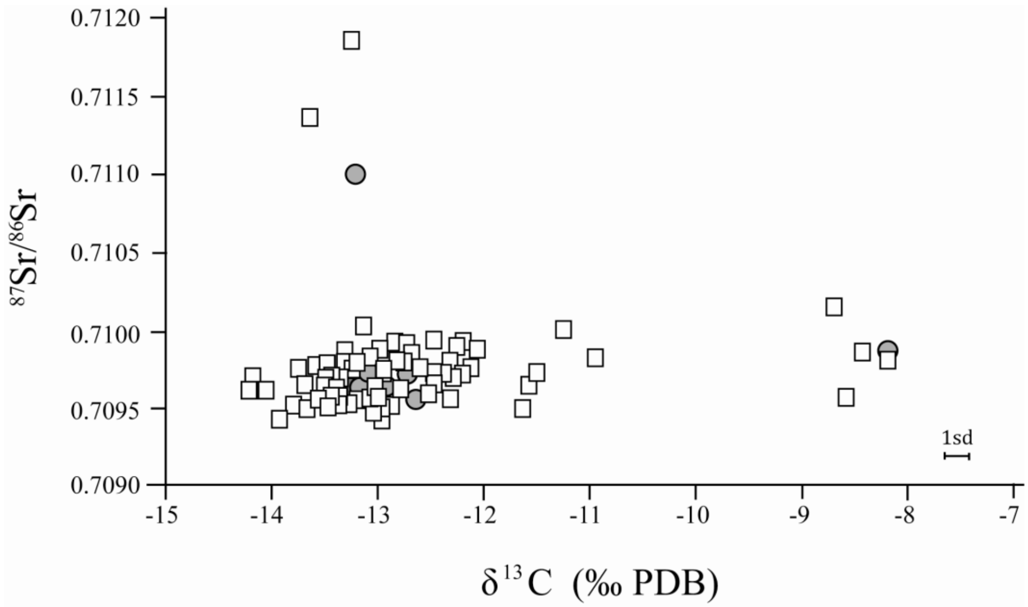


Figure 7: Isotopic results plotted with reference to Carabelli's cusp presence (grey circles) and absence (white squares)

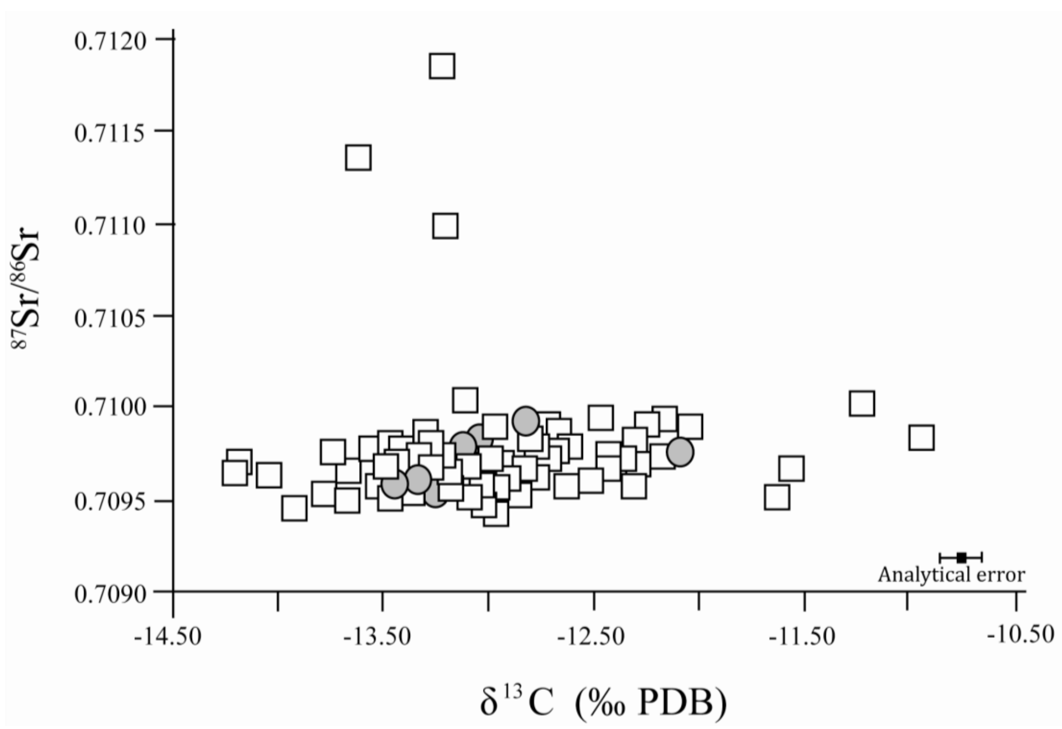


Figure 8: Isotopic results plotted to show the incidence of 6th cusps within the sample

Chi-squared testing for true morphometric outliers highlights seven individuals who are significantly morphologically different from the rest of the sample. Three further individuals were highlighted in the second iteration of the test that removes the individual from the group before calculating the mean (i.e. assumes them to be outliers). Results of this testing are given on figure 9.

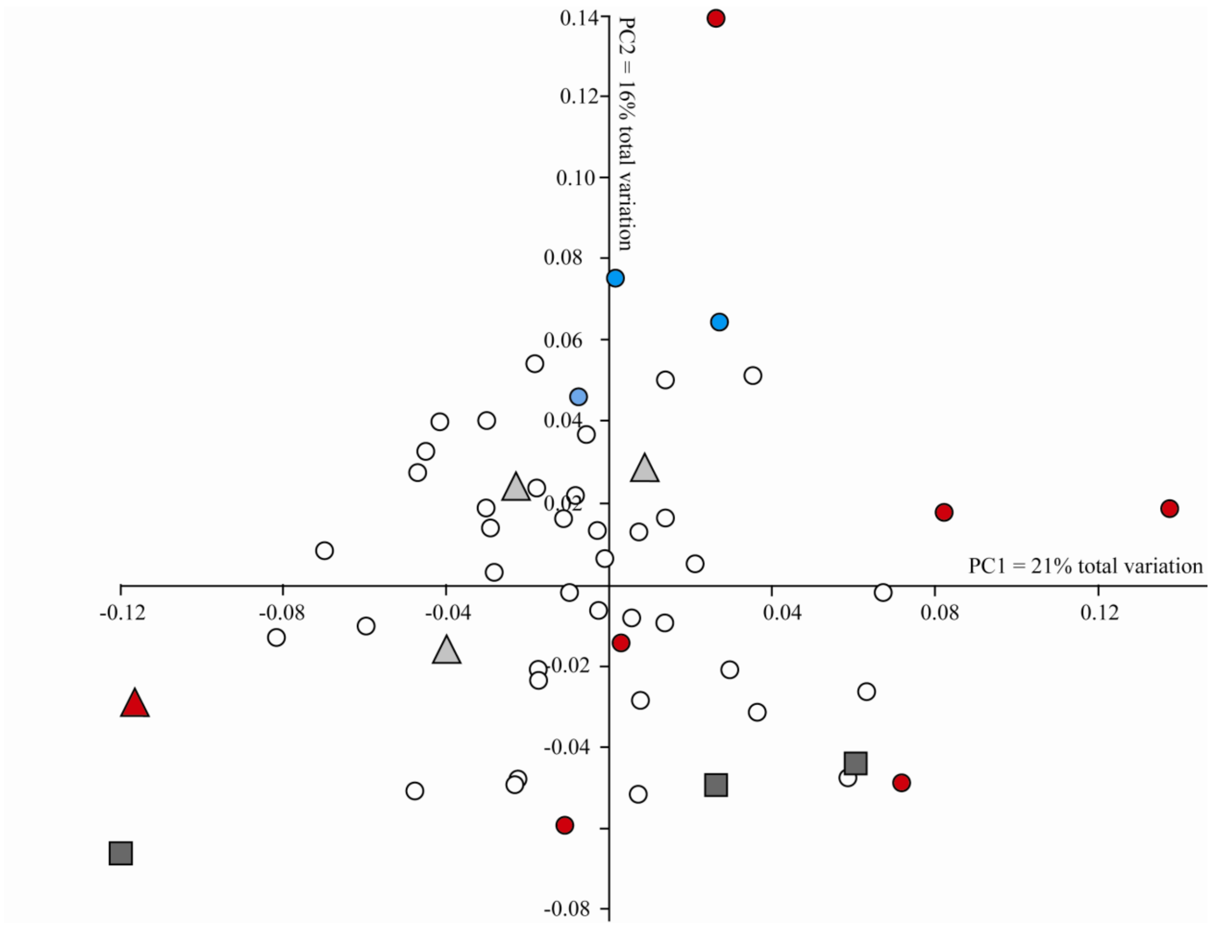


Figure 9: Results of Chi-squared testing, PC1 vs PC2 of procrustes distance data. Squares = carbon isotope outliers, triangles = strontium isotope outliers, circles = local isotope signatures. Red colour = morphological outlier in first iteration of Chi-squared testing, blue = additional outliers identified in the second form of Chi-squared testing.

A summary of all lines of evidence looked at in this study and how they correlate with each other is given in table 3.

name	**isotopic outlier**	**morphometric outlier**	**non-metric traits**
B10	No	No	EE
B11	No	No	EE
B14	No	1st test	slight shoveling
B145	No	No	EE
B155	No	1st test	EE
B161	No	No	slight shoveling
B17	No	No	slight shoveling
B178	No	No	EE; supernumary teeth
B188	No	No	slight shoveling
B194	Sr outlier	No	no shoveling
B196	no	No	carabelli's trait; EE
B20	no	No	EE
B201	no	No	slight shoveling
B21	slight C outlier	No	slight shoveling
B246	no	No	slight shoveling
B256	no	No	6th cusp; EE
B260	no	No	EE
B262	no	No	EE
B263	no	No	EE
B28	Sr outlier	1st test	slight shoveling

B290	No	No	no shoveling
B292	C outlier	No	EE
B294	No	No	EE; no shoveling
B30	No	No	slight shoveling
B304	slight C outlier	1st test	heavy shoveling
B306	No	No	no shoveling
B408	No	No	slight shoveling
B438	No	No	no shoveling
B440	Sr outlier	No	slight shoveling
B445	No	No	carabelli's trait
B449	No	No	EE
B454	No	No	no shoveling
B455	No	No	EE
B51	No	1st test	EE
B553	No	No	EE
B555	No	No	EE
B556	No	No	EE; no shoveling
B558	No	No	no shoveling
B569	No	No	EE
B571	No	2nd test	EE
B59	No	1st test	EE
B600	No	No	6th cusp
B609	No	2nd test	EE

B611	No	No	slight shoveling
B616	No	No	slight shoveling
B618	No	No	slight shoveling
B620	No	1st test	heavy shovelling; EE
B63	No	2nd test	EE
B631	No	No	slight shoveling
B633	No	No	no shoveling
B635	No	1st test	EE
B64	No	No	EE
B67	No	No	EE
B69	No	No	EE
B73	No	No	EE
B78	No	No	slight shoveling
B86	No	No	no shoveling
B9	No	No	slight shoveling
B93	No	No	EE
B97	No	No	EE

Table 3: Summary of isotopic, morphometric and non-metric trait data. EE = enamel extensions.

Discussion

One of the primary aims of this study was to evaluate whether osteological techniques could identify immigrant individuals through comparison with isotopic results. Results show, however, that individuals identified as long-distance migrants by strontium isotope analysis fell within local morphological variation.

The lack of differentiation of isotopic 'long-distance' migrants based on geometric morphometric results and non-metric traits is interesting in and of itself. It suggests that these migrants hail from populations genetically similar to the local population. This fits well with the findings of past researchers such as Turner (1992) and Pietrusewsky (2006) which suggests continous genetic admixture between the populations of the Southeast Asian peninsula.

Individuals who were carbon isotope outliers fell on the edges of normal morphological variation, but not in a consistent direction. This is difficult to interpret, but it is possible that differences in diet resulted in slightly different masticatory stresses on these individuals, which had epigenetic effects on the morphology of the cranium (cf. Strand Viðarsdòttir et al., 2002; Lieberman, 1995).

Comparison of isotopic results and non-metric trait occurrence show that no non metric-traits are restricted to the isotopic migrants. Interestingly, however, there are some correlations between individuals identified as *morphometric* outliers and non-metric trait frequency. Individuals B51, B304 and B620 are the most significant outliers in the morphometric dataset. The only two individuals with 'heavy' shovelling (3+ on the ASU scheme) in the dataset are B304 and B620. The presence of this trait could therefore indicate non-local origins.

Osteological differences between the Neolithic flexed and supine individuals

None of the Neolithic flexed burials were identified as morphological outliers using Chi-squared testing. Similarly no non-metric traits were found to be exclusive to the Neolithic flexed phase, and their overall trait frequencies were similar to those found in the supine burials. It is therefore concluded that there is little osteological evidence for considering the flexed phase a genetically distinct population.

This supports the findings of isotopic work at the site (King et al., 2013), which showed that there was no consistent dietary difference between the Neolithic flexed individuals and the supine burials, and the hypothesis that they were hunter/gatherers living alongside a distinct agricultural population does not seem to be supported.

Kinship groups and diet

Comparison of non-metric trait occurrence and isotopic results was undertaken to evaluate whether or not kinship groupings had an impact on diet (which is often a status indicator). Results show no correlations between any of the non-metric traits studied and diet (carbon isotope results). This indicates that if dietary restrictions were present at Ban Non Wat, as is often the case in a strict hierarchy, they were not related to kinship groups. Though this is not definitive evidence that kinship groups were not closely related to status it does slightly undermine the hypothesis that a rigid hierarchy was in place at Ban Non Wat.

Jar burials and morphological affinities

Two adult jar burials are present at Ban Non Wat, and both were analysed using geometric morphometric techniques in the course of this study. B28 has been established as a strontium isotope outlier, indicating his origins are definitely elsewhere. B292, on the other hand is a carbon isotope outlier, but falls within the local range for strontium isotope ratios. Chi-squared testing for morphological outliers identified B28 as having a significantly different cranial shape to the rest of the sample, indicating that he appears to originate from a genetically distinct community. B292, conversely, was not identified as a morphological outlier, perhaps indicating their origins lie genetically closer to the people of Ban Non Wat.

Future work

This study has shown isotopic migrants were difficult to identify using osteological techniques, probably because migration was occurring between genetically similar populations in prehistory. We propose that if variation in the cranial morphology of the surrounding archaeological sites (i.e. possible parent communities from which migration could occur) was fully quantified, this would make short distance migration easier to identify. Knowledge of the morphological differences between the sites of the UMRV would allow the use of discriminant function analysis, to evaluate which of the local populations an individual is most likely to belong to. Similarly a knowledge of regional variation in non-metric traits would allow the use of mean measure of divergence (MMD), or Mahalanobis distances to classify individuals into the population which they are most likely to belong to (cf. Irish, 2010). Employing these techniques, and further understanding short-distance migration processes, is a future avenue for research in the UMRV.

Conclusion

This study puts forward a method of testing for statistical outliers in terms of morphology. Using this method we have shown that one of the only two adult jar burials at the site has cranial morphological indicating origins in a different population. We have also shown links between the non-metric trait of heavy incisor shovelling and unusual cranial morphology which hint that this may be a migrant trait.

Use of osteological analysis in combination with isotopic results at the sites has also added weight to the argument that the flexed Neolithic burials do not represent a genetically distinct population to the supine individuals. In fact there seems to be genetic continuity between the two groups. This study also found no links between non-metric, geometric morphometric traits and isotopic results. This indicates that kinship group affinity had little impact on diet, and that for the most part isotopic outliers are likely to have a similar genetic background to local individuals.

18. Discussion

This thesis is the most comprehensive isotopic study conducted in the Upper Mun River Valley of northeast Thailand to date. As a result it has given new insight into the nature of prehistoric society in the region. Its goals included understanding of the level of migration occurring in the region, the nature of social organisation and the level to which subsistence strategy was homogeneous across the region.

18.1 The impact of migration

Strontium isotope analysis was undertaken primarily to address the question of whether or not migration was an important process in the development of social complexity in the UMRV. Results presented in section 13 show that only five individuals could be identified as long distance migrants through strontium isotope analysis. In addition to these individuals, carbon isotope analysis reveals five further outliers. The isotopic ratios of these individuals indicate the use of C_4 or marine resources, neither of which were likely to be available in the UMRV, they are therefore also interpreted as migrants.

In total there are therefore only 10 individuals from a sample of 144 that can be isotopically identified as migrants. Of these the majority are found in the Neolithic phases of the site, with only two isotopic outliers dated to the Bronze or Iron Age phases of the site. The lack of visible migration in the later phases of the site indicates that migration is unlikely to be a significant process leading to the onset of social inequality. Instead migrants are almost exclusively restricted to the Neolithic, particularly the flexed Neolithic phase. This represents initial occupation of the site and it is unsurprising that the first occupants of Ban Non Wat came from elsewhere.

These results support previous findings at the nearby sites of Ban Lum Khao (Bentley et al., 2009b) and Noen U-Loke (Cox et al., 2011), which found no evidence for migration. As the occupation of these sites does not begin until the Bronze Age, the lack of migrant individuals correlates well with the results presented here.

The results from the Upper Mun River Valley differ from those found at the coastal site of Khok Phanom Di (Bentley et al., 2007) and the more northern site of Ban Chiang (Bentley et al., 2005), where migration of female individuals is a prominent process in the early levels of the sites. It is interesting that evidence for matrilocality is present at Ban Chiang and Khok Phanom Di, but not in the UMRV which lies in between these two sites. It is important to note, however, that the homogeneous geology of the UMRV would not allow identification of short distance migrants (see section 8.7). Marriage exchanges are most likely to develop between nearby habitually interacting groups (Fix, 2004; Anthony, 1997), and thus such marriage exchanges would be isotopically invisible in the UMRV. The idea of matrilocality cannot, therefore, be ruled out based on isotopic results alone.

Higher levels of migration seen in the cemeteries of Khok Phanom Di and Ban Chiang may also be due in part to the earlier initial occupation of these sites (Higham & Thosarat, 2004; Pietrusewsky & Douglas 2002), if we compare contemporaneous phases the difference is not so marked. In the case of Khok Phanom Di it is also probable that the coastal nature of the site meant it had trade links with settlements further afield (Higham & Thosarat, 1994;

Bentley et al., 2007) and was a more easily accessible site for migrants to gravitate towards than those in the UMRV.

It is apparent, though, that migrants were few in the prehistoric UMRV, and are therefore unlikely to have had a great impact on social development. The results of this study are further support for that the idea that social complexity in Southeast Asia cannot have been achieved without external input (Coedes, 1969) is completely unjustified.

18.2 Social organization and the hierarchy/heterarchy debate

One of the most contentious issues in current Southeast Asian archaeology is whether prehistoric societies were fully hierarchical. This debate has been detailed in section 5.5, and reflects the growing concern in archaeology that early models of 'progression' towards social complexity (Service, 1962) may not be valid in all contexts.

In order to establish whether or not isotopic results combined with osteological evidence could be useful in resolving this debate, hypothetical models were established reflecting the possible forms of social organization. These models are explained fully in section 13. They centre around the idea that rigid hierarchy will result in more obvious isotopic clustering relating to proscribed marriage exchanges and diet. It was also hypothesized that there should be a correlation between isotopic results and mortuary wealth if status was related to place of origin or diet.

In reality isotopic results formed a continuum, indicating a lack of well-defined groups based on diet, and no obvious external groups representing established marriage exchanges.

There was also no correlation between strontium isotope results and mortuary wealth, indicating that external origins did not affect status. These results do not fit well with the expected results for rigid hierarchy, the current interpretation of social organization at Ban Non Wat (Higham & Kijngam, 2009).

In addition, osteological analysis shows no correlation between diet and genetic relatedness (section 16). Hierarchical societies are usually based on inherited rank, and therefore kinship groups will share the same status. This means that diet will often be similar between related individuals. This pattern is not seen at Ban Non Wat, adding further weight to the idea that a rigid hierarchy was absent.

It seems apparent that clear divisions in society in terms of wealth, diet and kinship groups were not present at Ban Non Wat. This is more in keeping with the idea of a heterarchical society, but the possibility that a more flexible hierarchy was in operation cannot be discounted.

18.3 Regional differences across the UMRV

Heterarchical social organization is based on household production centres and can result regional differences in culture (e.g. White & Eyre, 2011). The final goal of this research was to establish whether or not there were differences in carbon isotope results across the Upper Mun River Valley, perhaps reflecting this cultural pluralism in terms of subsistence strategy. There are examples of regional differences in the uptake of new technologies such as Bronze in Western Thailand (Glover, 1991), or level of involvement in trade (White, 1995). There has also been suggestion that mixed economies may have persisted beyond the introduction of agriculture in Thailand (Bellwood, 1996). Therefore small-scale differences in subsistence across the UMRV are not implausible.

Investigating whether or not cultural diversity was the case involved comparison of isotopic results from Ban Non Wat with those obtained in previous studies at Noen U-Loke (Cox et al., 2011) and Ban Lum Khao (Bentley et al., 2009b). Results of this aspect of the study are detailed in section 14, but in essence reveal that Ban Non Wat was less reliant on rice agriculture than Noen U-Loke and Ban Lum Khao. This lack of uniformity across the valley is echoed in the differences in mortuary wealth between the sites which had led Higham & Kijngam (2011) to suggest significant disparities in wealth between sites of the UMRV during prehistory. It also links well with the idea that the agricultural 'revolution' in Southeast Asia was not the swift and uniform process seen in Europe, but instead a gradual transition during which time matrilocal communities and mixed economies persisted (Bentley et al., 2005; Bellwood, 1996).

18.4 Climate and subsistence

This study has revealed that oxygen isotopes in teeth can be used as an environmental proxy in Southeast Asia (section 15). The changes seen through time reflect the changes traced in independent climatic proxies such as stalactites and foraminifera (Wang et al., 2005; Lückge, 2001). The advantage of looking at climate change in dental enamel for the archaeologist, however, is that it can be analysed concurrently with carbon isotopic ratios. This means climate can be directly correlated to subsistence change, giving the archaeologist insight into coping strategies put in place by the prehistoric population.

In the UMRV it appears that a gradual decrease in rainfall occurs throughout occupation. This is correlated with a decrease in reliance on rice agriculture from the Bronze Age through to the Iron Age. The isotopic results of this study match well with the geomorphological findings of Boyd & McGrath (2001; McGrath & Boyd, 2001; Boyd, 2008), which show re-routing of river systems and the construction of moats in order to control water during late Prehistoric occupation of the valley. The results also corroborate the theory put forward by Boyd & Chang (2010) that rice became more difficult to grow during the Iron Age in the UMRV, which increased its prestige value and ritual importance.

The pattern of decreasing reliance on rice agriculture is not just a regional phenomenon. Climate change would have affected the entire Southeast Asian peninsula, and it is therefore unsurprising that isotopic work at the more northern site of Ban Chiang (King, 2006) also shows a shift away from pure C_3 crop use.

Currently we cannot know which resources the people of Ban Non Wat chose to supplement their diet when rice agriculture could not suffice. Both increased consumption of meat and use of C_4 crops would cause the shift seen in the isotopic results of this study. Currently there is no evidence for C_4 crops being present in the UMRV, but phytoliths of the most common C_4 crop are far less easily retrieved from archaeological contexts than those of rice (Weber et al., 2010). Thus it often goes unrecognized in the archaeological record, and may well be revealed when further archaeobotanical work is conducted in the area (Castillo, pers. comm.). Supplementation of the diet by millet was King & Norr's (2006) interpretation of a carbon isotope shift at Ban Chiang, so it is not implausible that this was also the case at Ban Non Wat.

18.5 Adding to the 'Big Picture' in the UMRV

The over-arching goal of this study was to increase understanding of processes leading to social complexity in the Upper Mun River Valley in northeast Thailand. This has been addressed by looking at the possibility of external influences such as migration events and environmental change, the relationships between kinship, diet and wealth, and the homogeneity (or lack thereof) of culture across the valley.

In summary this study has shown a lack of migration into Ban Non Wat, except in the earliest phases of occupation. Combined with previous isotopic work it shows that social development is highly unlikely to have been extrinsically triggered.

Dietary isotope work conducted as a part of this study also gives several important insights into the nature of prehistoric society in the UMRV. A lack of correlation between dietary isotopes, wealth and kinship groups shows that dietary restrictions are unlikely to have been in place in Ban Non Wat, hinting that an inflexible hierarchy was not present. Change in dietary isotope ratio through time can help pinpoint the timing of intensification of rice agriculture (the second Bronze Age phase at BNW), and shows its correlation to the period of maximum social stratification. Dietary changes also appear to be linked to climate change, showing the impact of environmental change on subsistence strategy. Finally, significant differences in dietary isotope ratio between the sites of the UMRV reveal the possibility that rice agriculture was not uniformly taken-up by different sites within the valley.

18.6 Methodological Findings

An additional goal of this research was to establish whether osteological techniques, such as non-metric trait and geometric morphometric analysis, might be useful in the identification of migrant individuals.

There are a number of limitations to the use of strontium isotope analysis to identify non-local individuals. Especially relevant to this study is the problem of homogeneous geology i.e. the UMRV and surrounding valleys are all formed of arkose sandstone, giving a uniform $^{87}Sr/^{86}Sr$ ratio of ~ 0.7097. This means that short-distance migration is effectively invisible, though it was almost certainly a significant process in prehistory (Fix, 2004; Anthony, 1997). Also relevant to this study is the issue of destructive analysis. Isotopic analysis is, by nature, destructive, as enamel must be removed from the tooth and dissolved in order to measure isotopic ratios. In this study teeth could not be analysed unless they had an antimere, and did not exhibit any dental pathology. This meant that important osteological information was not lost when the tooth was partially destroyed, but it also led to non-uniformity in the tooth sampled which is less than ideal. These problems in particular mean that having another proxy for population affinity would be useful.

In order to investigate whether geometric morphometrics could be used as an alternative to isotopic analysis geometric morphometric analysis was conducted at Ban Non Wat (section 16). Building on the work of Martinez – Abadias et al. (2005), and Ross et al. (2004), this study showed that some long-distance migrants may well be identifiable without the need for destructive isotopic work. It revealed that jar burial may be indicative of non-local origins, but that other isotopically identified long-distance migrants may have come from genetically very similar populations.

Use of osteological analysis in combination with isotopic results at the sites has also added weight to the argument that the flexed Neolithic burials do not represent a genetically distinct population to the supine individuals. In fact there seems to be genetic continuity between the two groups. This study also found no links between non-metric, geometric morphometric traits and isotopic results. This indicates that kinship group affinity had little impact on diet, and that for the most part isotopic outliers are likely to have a similar genetic background to local individuals.

Overall geometric morphometrics appears to have potential to, at the very least, identify individuals to target for isotopic analysis i.e. suspected migrants. Full knowledge of possible populations of origin, and their cranial morphology is required in order to be able to definitively separate migrants. In the archaeological record, however, the potential for this being the case is limited.

18.7 Further work

In light of the findings from this initial study into population affinity from cranial morphology it is possible that short distance migration could be identified if differences in cranial morphology from nearby settlements was fully characterized. It is suggested that a large-scale geometric morphometric analysis of Ban Lum Khao, Noen U-Loke and Ban Non Wat may be an area for future research. Knowledge of short-distance migration would help to complete the picture of prehistoric interaction across the valley.

This study has also shown the enormous potential for tracing climate change alongside dietary differences. Here only bulk isotopic samples were used, and mortuary phases considered as slices of time through which to assess change. The technique of micromilling, however, allows sampling within a single tooth to give a record of change as the tooth was mineralizing. It would allow fine-scale resolution of both dietary and climatic change, giving new insight into climatic fluctuations and the impact they had on diet in the past. This technique has been used by Krigbaum (2012) in Niah Cave individualsto great effect, and it could be equally well applied in the UMRV to give more complete description of change over time.

19. Conclusion

The rise of social complexity, in any area, is a multi-faceted process. Here just some of the processes which may be relevant to social complexity in the Upper Mun River Valley of Thailand have been considered. Overall this study has shown that there are links which can be made between the rise of obvious social differentiation and an increased reliance on rice agriculture (section 15), and that this complexity is likely to have arisen intrinsically (section 13). Isotopic evidence from Ban Non Wat adds weight to the argument made for social diversity in Southeast Asia, and reveals differences in diet and subsistence between sites (Section 14), which links well with White's (2011) ideas of sub-regional cultural groupings.Isotopic results also add evidence which can be used in the debate over hierarchical and heterarchical organisation in the region, and osteological evidence also suggests there is little difference between the Neolithic flexed individuals at the site and the supine burials, indicating a continuity of population between the two burial types.

The use of geometric morphometric analyses, non-metric trait recording and isotopic studies at Ban Non Wat has shown the extra depth of information that can be gleaned from using these techniques in combination. At Ban Non Wat, for instance geometric morphometric techniques show links between unusual dental non-metric traits and outlying cranial morphology which may indicate short-distance migration. This initial study has paved the way for future research in the area using these new techniques, of particular interest would be quantifying the morphology of nearby sites to establish the extent of short-distance migration.

Appendix 1 – Excavation plans

Plans showing the position of burials in each of the mortuary phases at Ban Non Wat, adapted from Higham & Kijngam (2009). Those analysed as part of this study are highlighted with grey circles.

Figure 1: Neolithic flexed burials

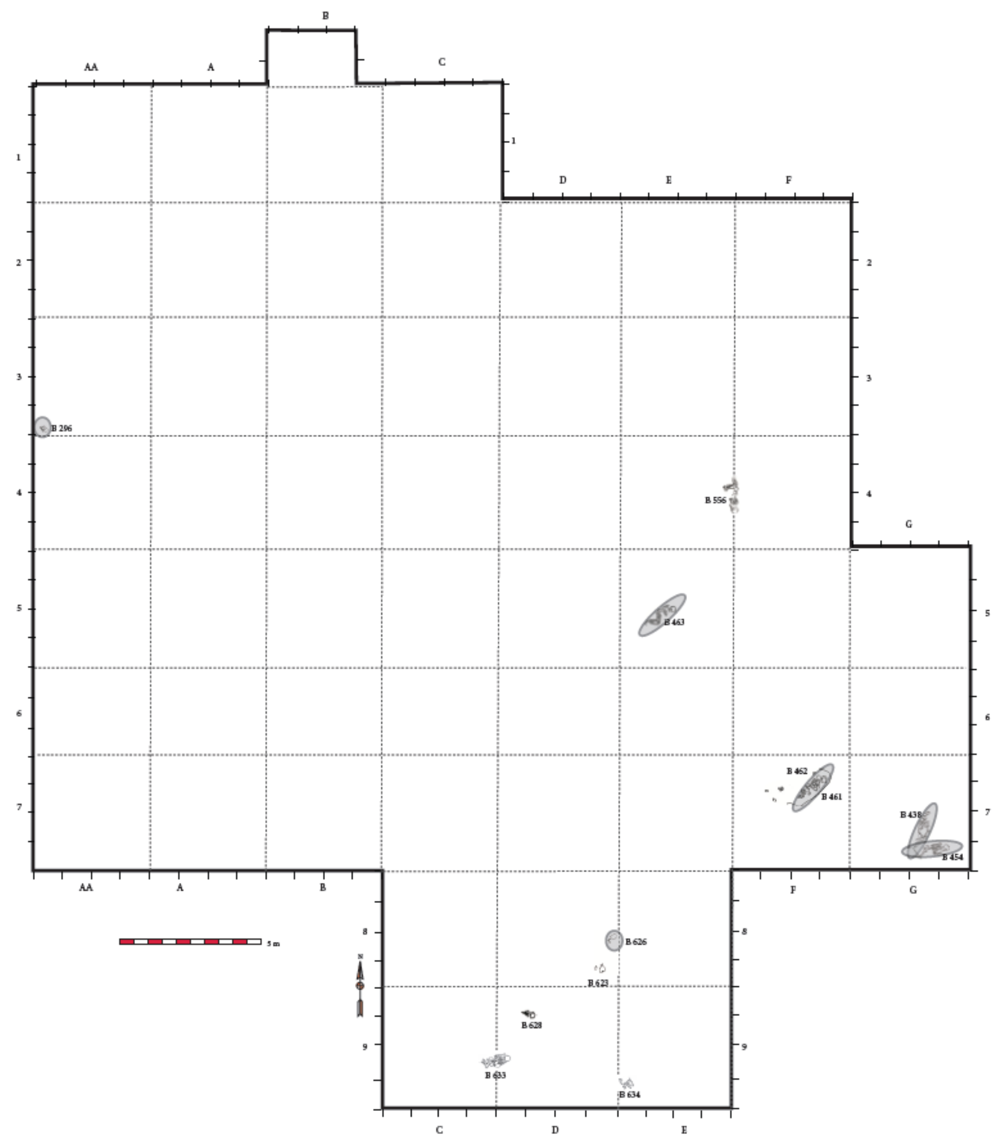


Figure 2: Neolithic 1 burials

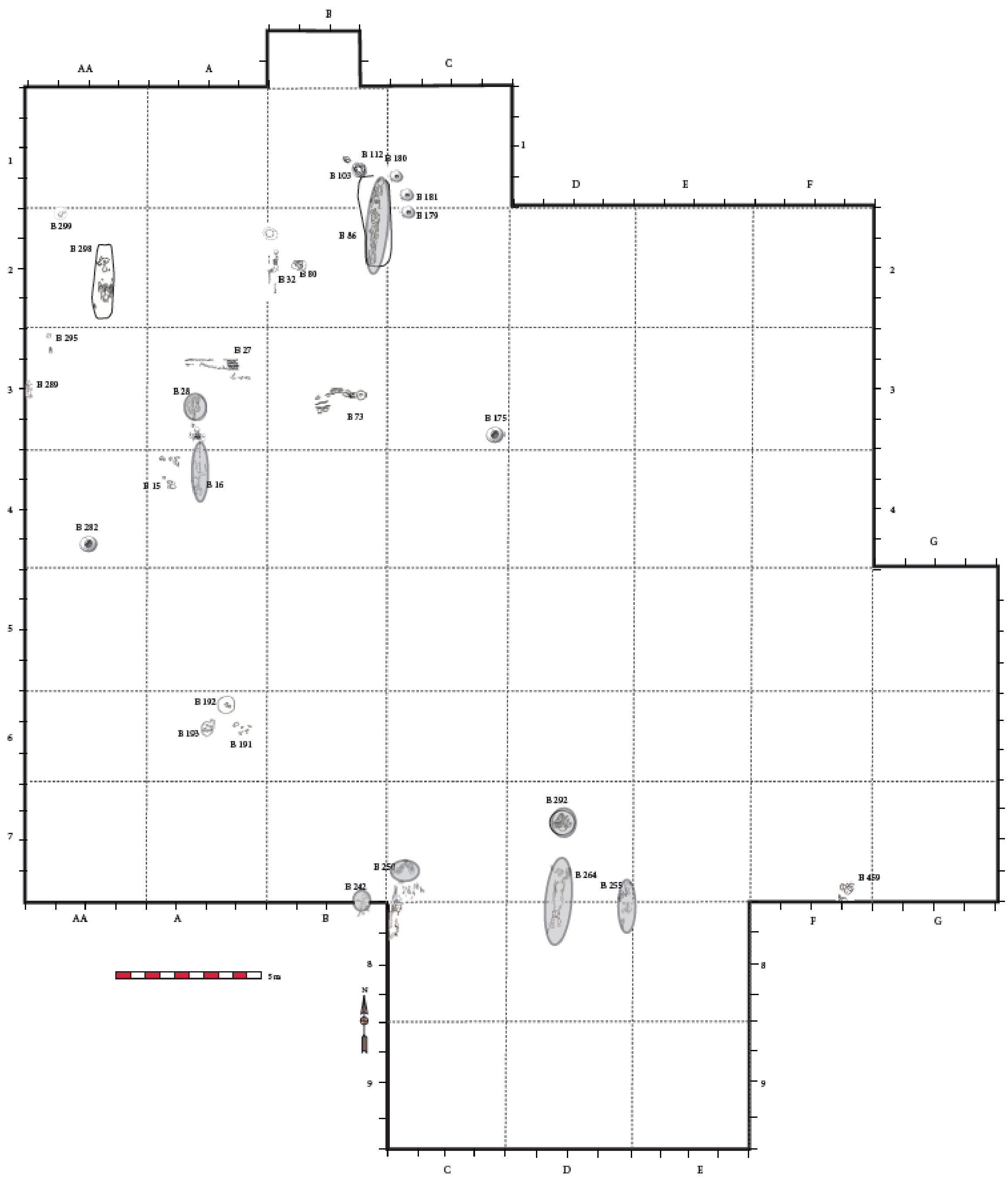


Figure 3: Neolithic 2 burials

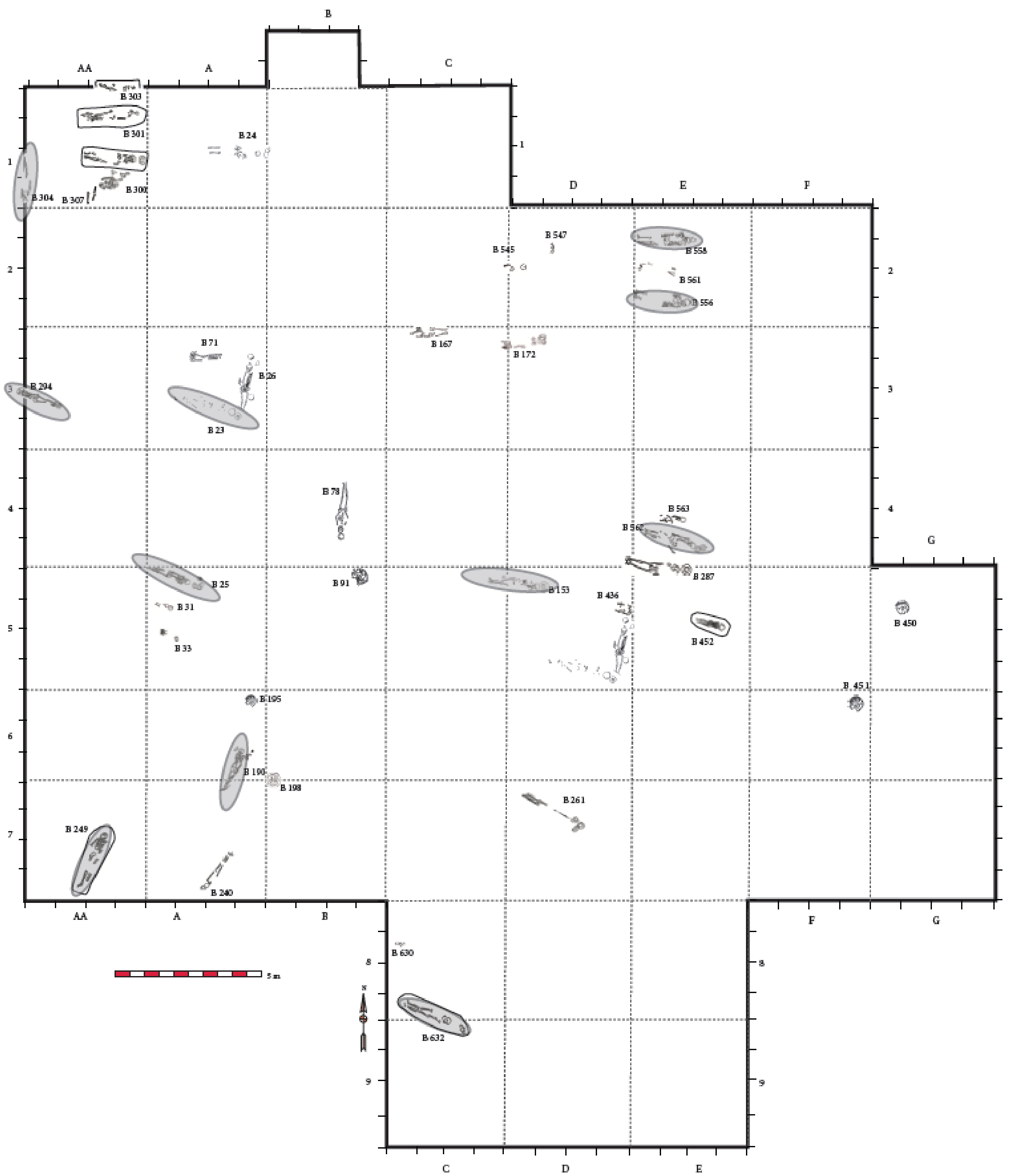


Figure 4: Bronze Age 1 burials

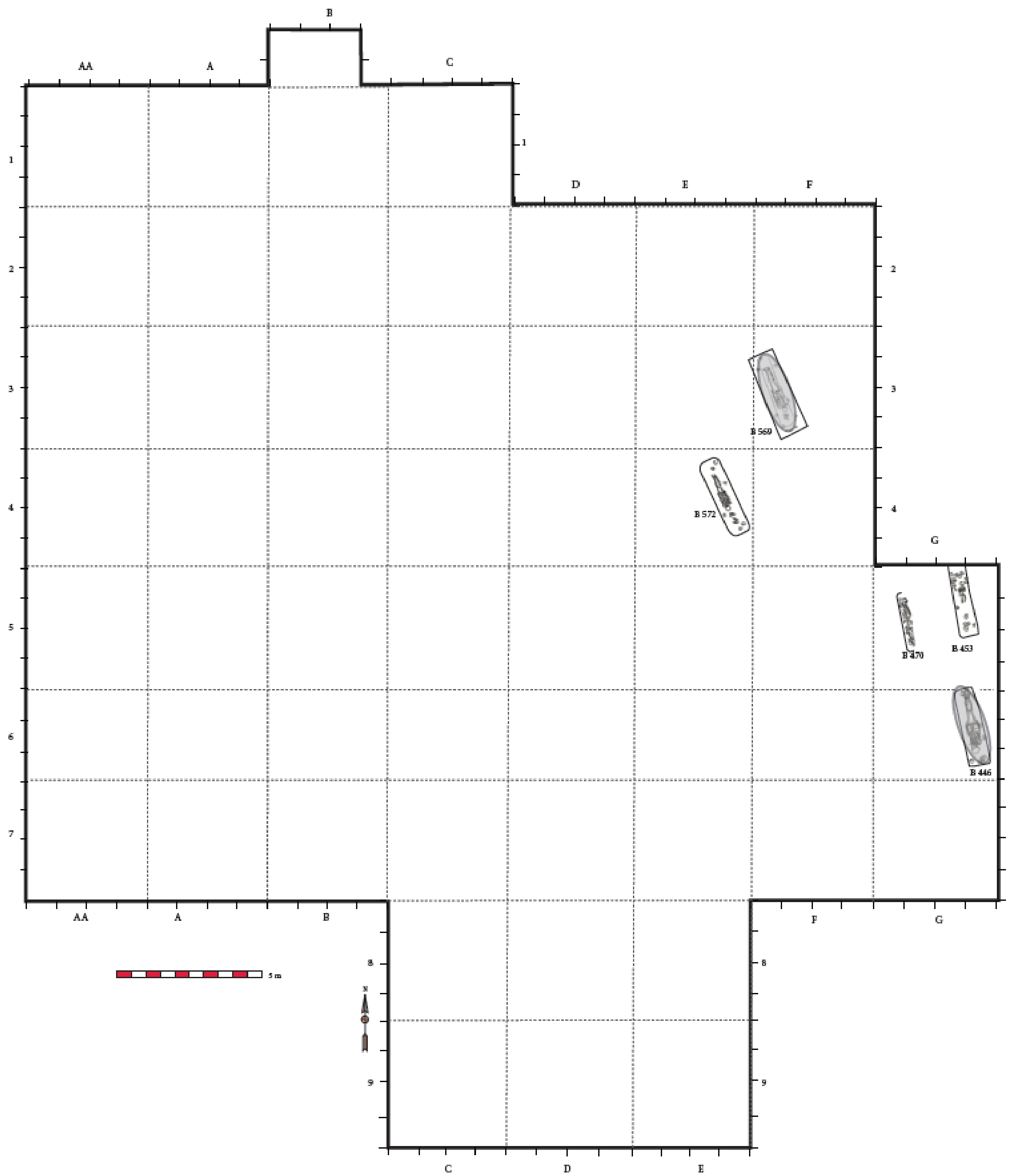


Figure 5: Bronze Age 2 burials

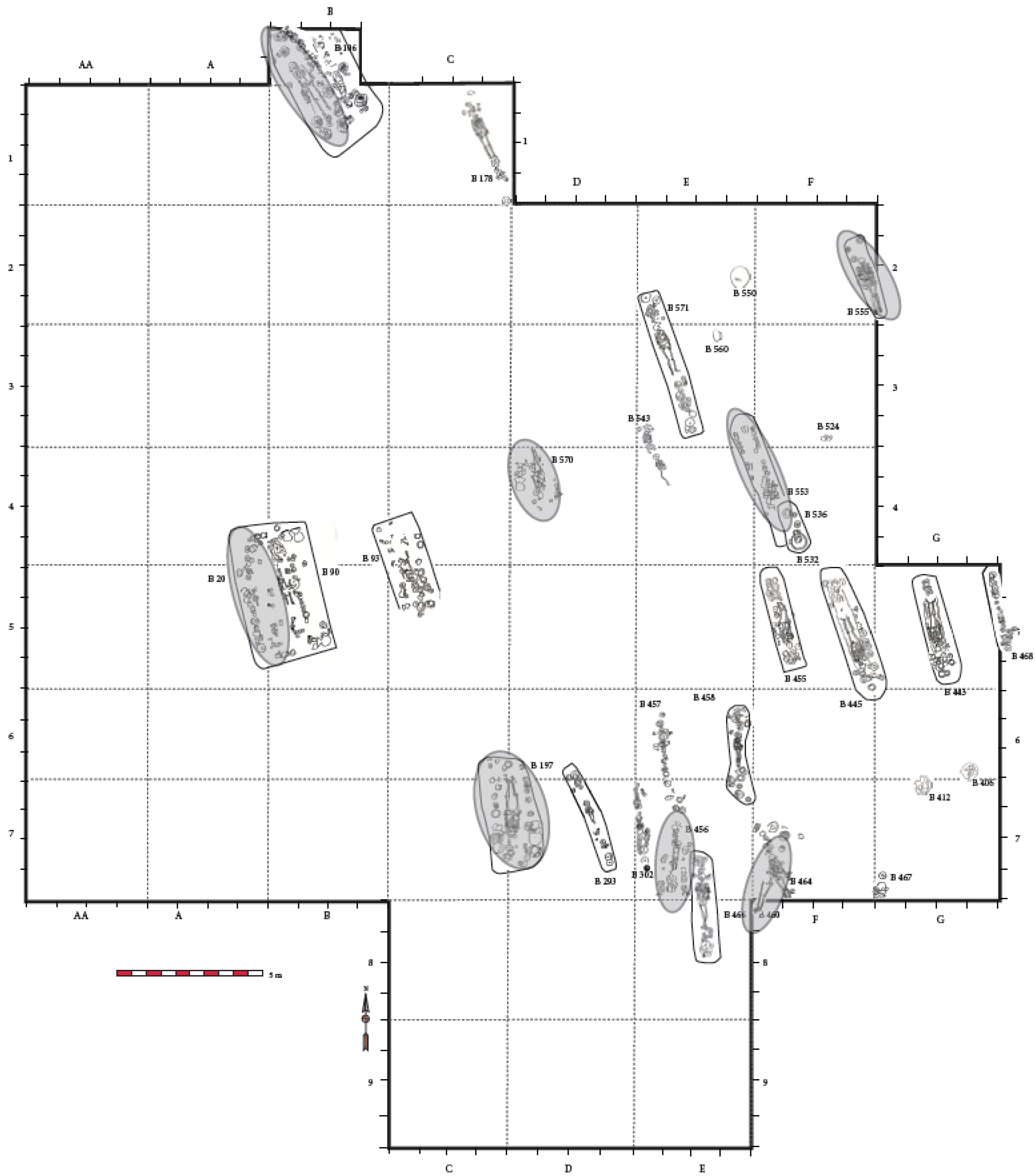


Figure 6: Bronze Age 3 burials

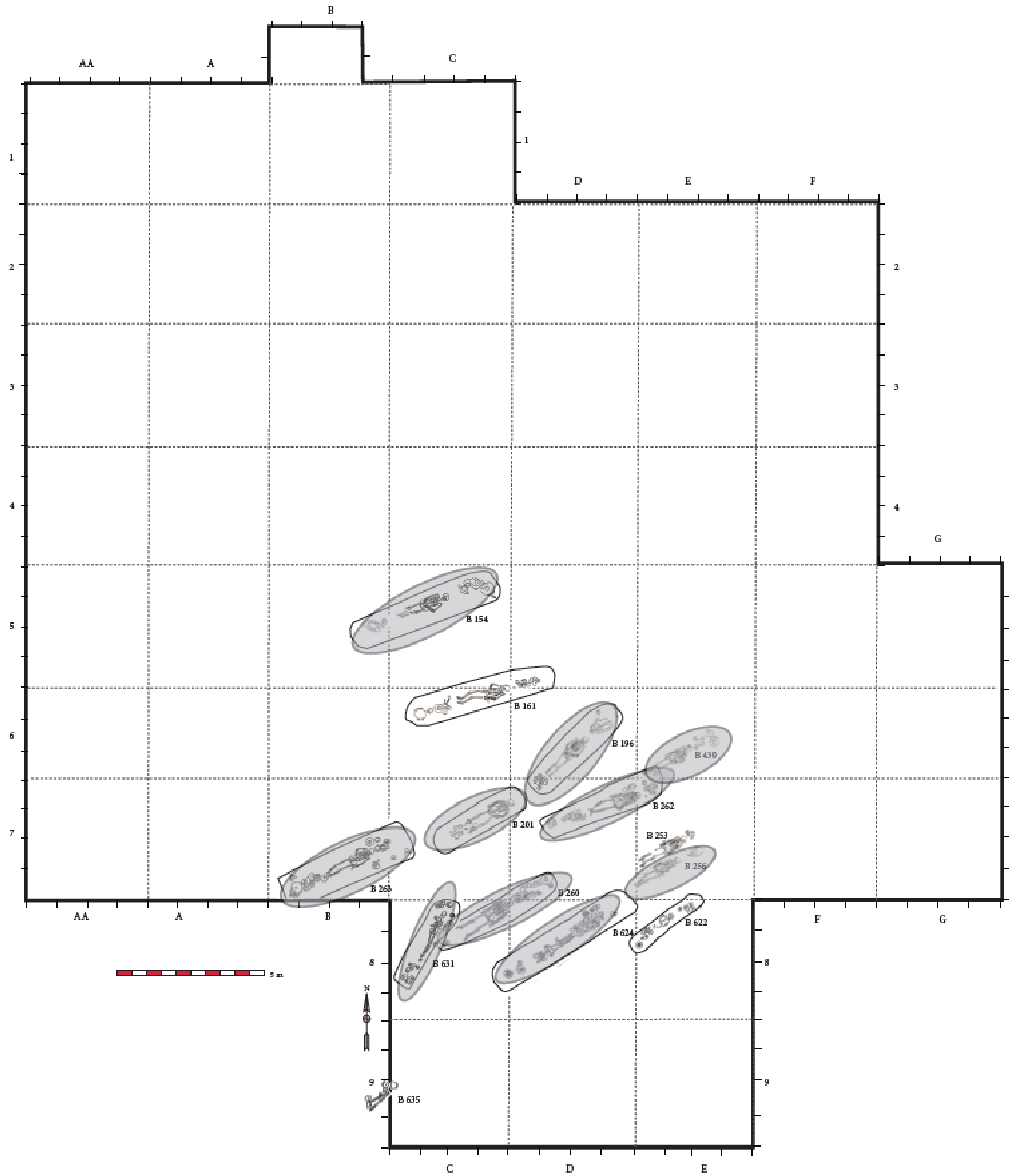


Figure 7: Bronze Age 4 burials

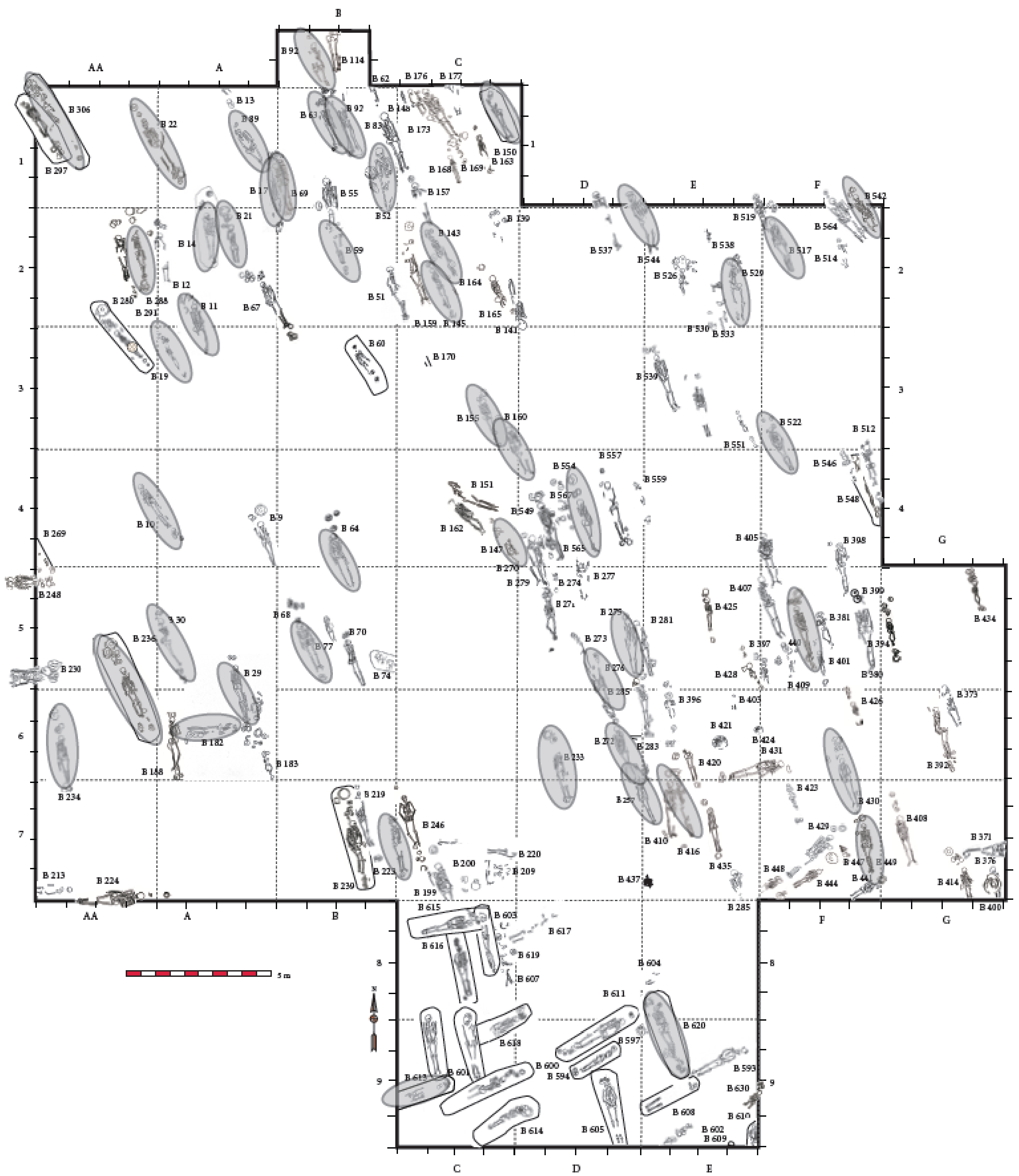


Figure 8: Bronze Age 5 burials

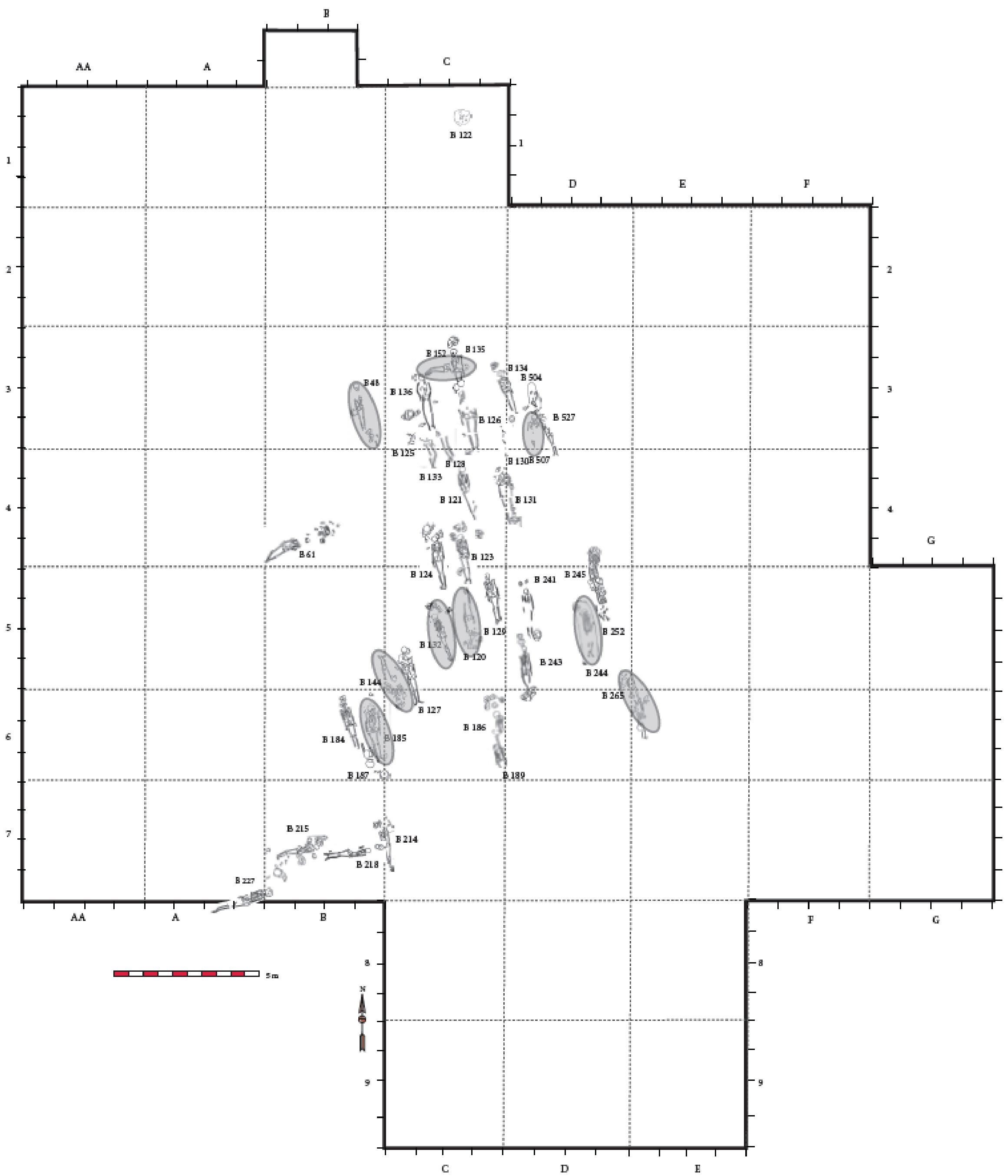


Figure 9: Iron Age 1 burials

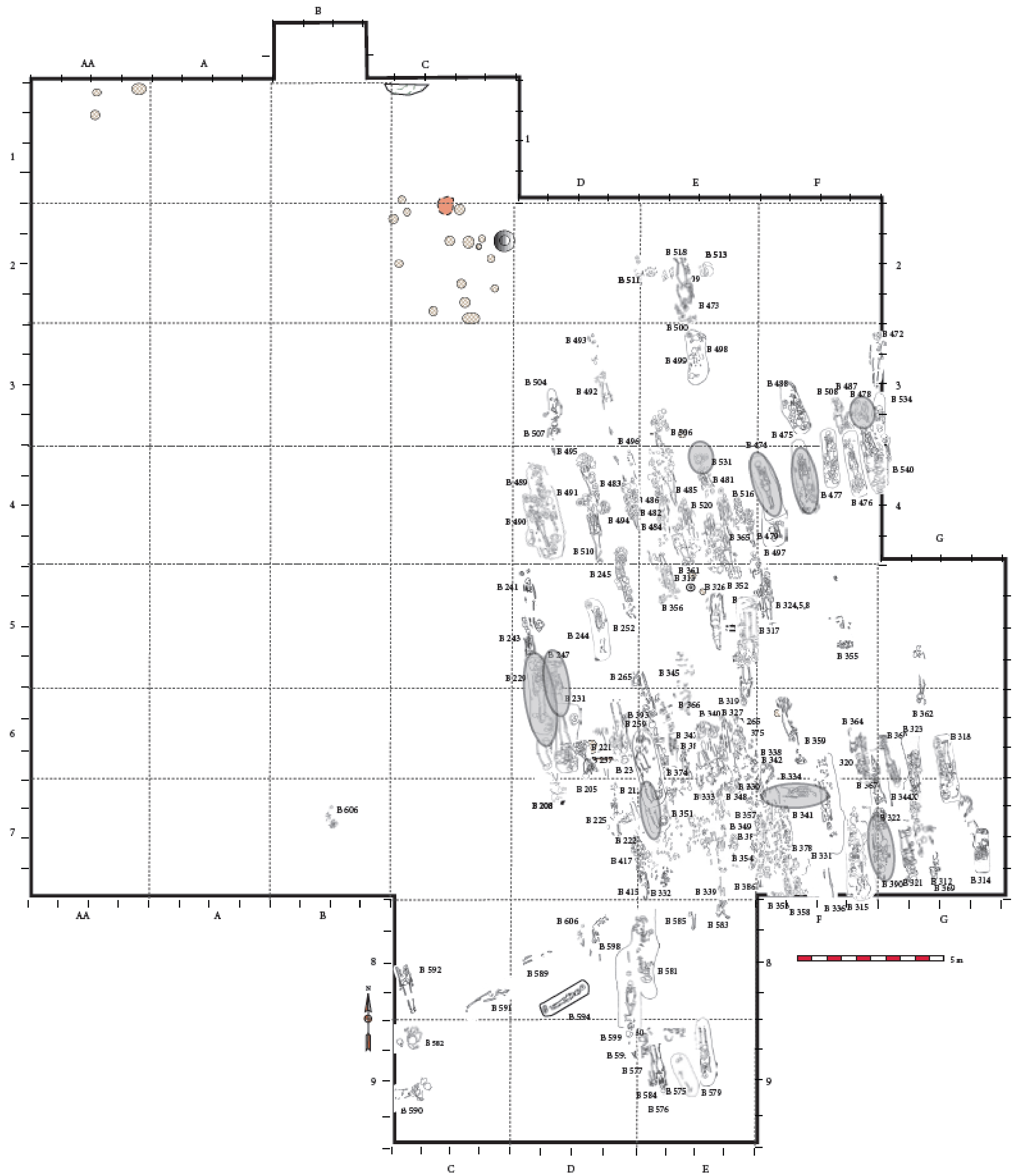
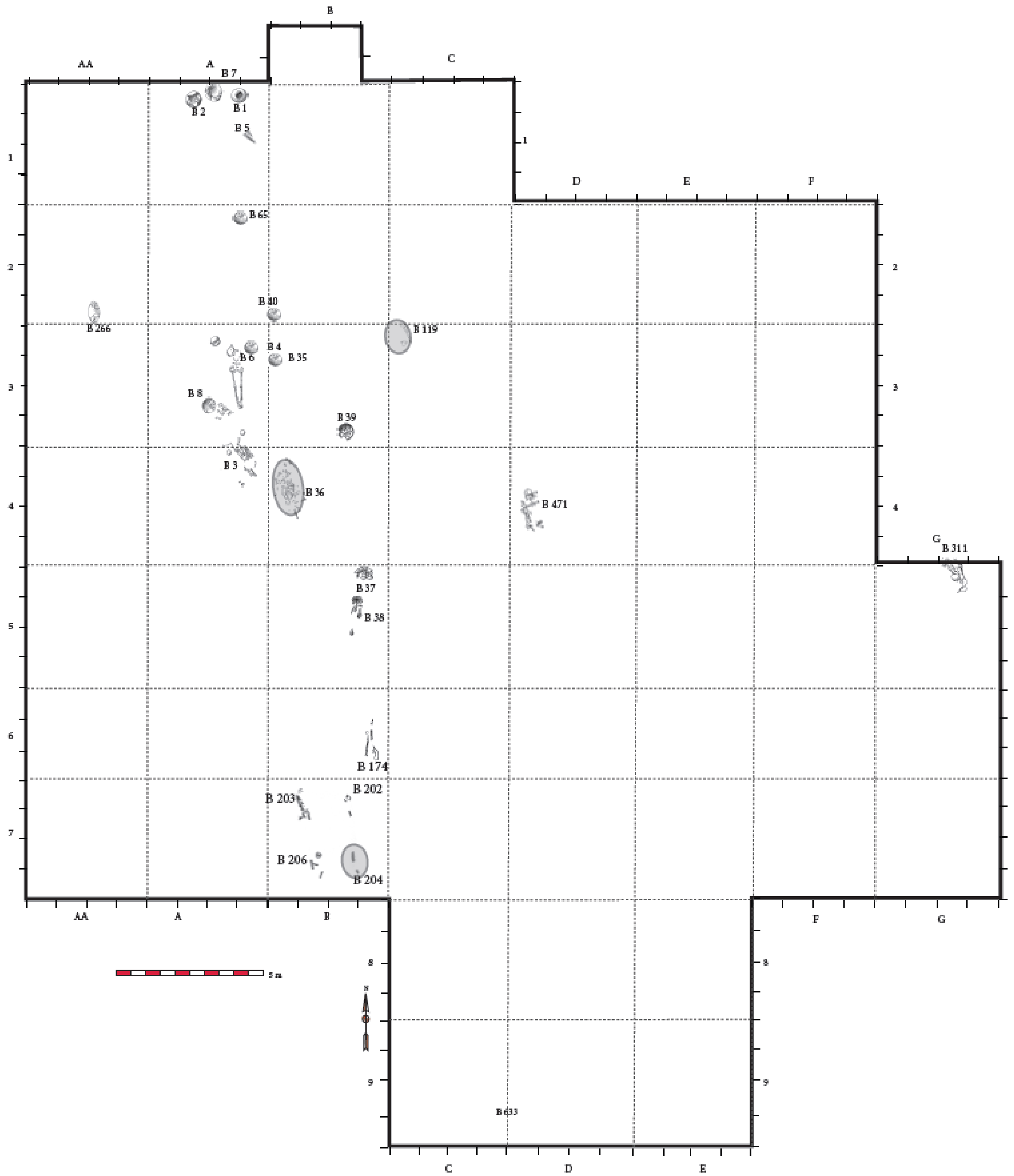


Figure 10: Iron Age 2 burials



Appendix 2 – Isotopic Results

Table 1 (overleaf): Results of all isotopic work undertaken including tooth sampled, demography information, and standard error. These results comprise the supplementary material referred to as supplementary table 1 in manuscripts 1-3 of this thesis.

The first superscript number following burial numbers indicate the batch the samples were run in during strontium isotope analysis, the second carbon and oxygen analysis batch numbers. Average NBS987 values for each of the Sr runs are as follows: 1 = 0.710275 ± 9 (2s.d, *n* = 12), 2= 0.710258 ± 15 (2s.d. *n* =11), 3 = 0.710234 ± 11 (*n* = 6), 4 = 0.710250 ± 8 (*n* = 6), 5 =0.710254 ± 11 (*n*= 9), 6 = 0.710264 ±6 (*n* =9), 7= 0.710266 ± 12(*n* = 16), 8 =0.710270 ± 12 (*n* = 10), 9 =0.710264 ± 15 (*n* = 11). Strontium isotope ratios for each of the samples were normalized based on the offset of these average NBS987 values from the accepted value of the standard. In this table both isotopic ratios and standard error values have been rounded to 5dp.

Carbon and oxygen isotope analysis was conducted in eight batches, indicated by second superscript number. Mean DCS01 results for each batch are as follows: 1 = -35.58‰ ± 0.05 (1sd. δ^{13}C PDB) and 13.14 ‰ ± 0.05 (1sd. δ^{18}O SMOW)*n* = 14; 2 = -35.60‰ ± 0.03 (1sd. δ^{13}C PDB) and 13.15 ‰ ± 0.05 (1sd. δ^{18}O SMOW) *n* = 13; 3 = -35.66‰ ± 0.03 (1sd. δ^{13}C PDB) and 13.16 ‰ ± 0.04 (1sd. δ^{18}O SMOW) *n* = 7; 4 = -35.55‰ ± 0.06 (1sd. δ^{13}C PDB) and 13.09 ‰ ± 0.12 (1sd. δ^{18}O SMOW) *n* = 6; 5 = -35.54‰ ± 0.04 (1sd. δ^{13}C PDB) and 13.14 ‰ ± 0.10 (1sd. δ^{18}O SMOW) *n* = 4; 6 = -35.54‰ ± 0.08 (1sd. δ^{13}C PDB) and 13.19 ‰ ± 0.13 (1sd. δ^{18}O SMOW) *n* = 4; 7 = -35.57‰ ± 0.03 (1sd. δ^{13}C PDB) and 13.13 ‰ ± 0.09 (1sd. δ^{18}O SMOW) *n* = 8; 8 = -35.58‰ ± 0.05 (1sd. δ^{13}C PDB) and 13.15 ‰ ± 0.07

(1sd. $\delta^{18}O$ SMOW) $n = 6$. Repeat measurements of samples gave analytical error of ±0.18‰ (1sd) on sample measurements. This means that while results are reported to 2dp, they are accurate only to 1dp.

Burial number	Ratio 87Sr/86Sr	2S.E.	d^{13}C$_{V\text{-}PDB}$	d^{18}O$_{V\text{-}PDB}$	d^{18}O$_{V\text{-}SMOW}$	Tooth sampled	Age	Sex	Mortuary Phase
10[5,5]	0.70955	0.00001	-13.48	-3.89	26.90	45	mid	M	BA4
11[5]	0.70962	0.00001	Not enough material for analysis			34	old	M	BA4
14[8,4]	0.70958	0.00001	-12.92	-4.07	26.71	28	mid	M	BA4
16[2,6]	0.70994	0.00001	-12.19	-4.00	26.78	37	young-mid	F?	N1
17[2,6]	0.70960	0.00002	-13.36	-3.15	27.66	24	mid	M	N2
20[6,3]	0.70975	0.00001	-13.26	-4.04	26.74	46	unknown	?	BA2
21[6,4]	0.70965	0.00001	-14.05	-4.85	25.91	46	mid-old	F	BA4
22[5]	Not enough material for analysis		-12.62	-3.99	26.80	unknown	unknown	F	BA4
23[7,5]	0.70973	0.00001	-12.18	-4.25	26.53	47	unknown	?	N2
24[7,4]	0.70973	0.00001	-12.72	-4.44	26.33	44	unknown	M	N1
25[6,2]	0.70963	0.00001	-13.41	-5.64	25.10	48	mid-old	M	N2
26[6,5]	0.70989	0.00001	-12.25	-3.64	27.16	26	young	F?	N2
28[4,5]	0.71001	0.00001	-11.24	-5.00	25.76	36	old	M	N1
29[8]	0.70962	0.00001	Not enough material for analysis			14	mid	M?	BA4
30[2,6]	0.70954	0.00001	-13.36	-4.15	26.63	18	mid-old	F	BA4
36.1[9,8]	0.70994	0.00001	-12.48	-3.89	26.90	Molar frag	old	F?	IA2
36.2[9,8]	0.70981	0.00001	-13.09	-2.57	28.26	Molar frag	mid-old	M	IA2
48[7]	0.70961	0.00001	Not enough material for analysis			24	young-mid	M?	BA5
52[6]	Not enough material for analysis		-13.11	-3.40	27.40	31	young-mid	F	BA4
59[9,8]	0.70959	0.00001	-13.50	-4.40	26.38	25	?	?	BA4
63[5,7]	0.70971	0.00001	-13.19	-3.69	27.10	15	unknown	M	BA4
64[8,1]	0.70951	0.00001	-12.96	-3.50	27.30	45	old	M	BA4
68[5,4]	Not enough material for analysis		-13.16	-4.53	26.24	24	young	F	BA4
69[8,4]	0.70954	0.00001	-13.18	-3.49	27.31	28	young	M	BA4
86[3,1]	0.70985	0.00001	-12.71	-3.94	26.85	26	young	M	N1
89[6,3]	0.70951	0.00001	-13.04	-3.23	27.58	23	young-mid	F?	BA4

92[6,7]	0.70960	0.00001	-13.34	-5.67	25.07	42	young	F	BA4
97[7,2]	0.71184	0.00001	-13.23	-4.25	26.53	15	unknown	M?	BA2
119[9,8]	0.70968	0.00001	-12.46	-2.88	27.94	38	mid-old	?	IA2
120[6,5]	0.70962	0.00001	-12.53	-3.88	26.91	45	mid	?	BA5
126[6]	0.70968	0.00002	Not enough material for analysis			15	young	M?	BA5
132[8,8]	0.70956	0.00001	-13.15	-3.28	27.53	15	young	F?	BA5
143[6]	0.70953	0.00003	Not enough material for analysis			41	old	M	BA4
144[6]	Not enough material for analysis		-12.67	-2.79	28.03	34	young	F?	BA5
145[6]	Not enough material for analysis		-13.41	-5.62	25.11	18	mid-old	M	BA4
150[7]	0.70956	0.00001	Not enough material for analysis			41	unknown	M?	BA4
152[8]	0.70971	0.00001	Not enough material for analysis			25	young	F	BA5
153[8,7]	0.71096	0.00001	-13.21	-4.02	26.76	28	mid-old	F?	N2
154[5,2]	0.70965	0.00002	-13.27	-4.24	26.54	38	unknown	F	BA3
155[7,6]	0.70963	0.00001	-13.00	-3.98	26.81	38	unknown	M	BA4
160[6,5]	0.70958	0.00001	-13.37	-2.47	28.36	32	old	F	BA4
166[5]	Not enough material for analysis		-12.77	-3.95	26.84	45	unknown	F	BA4
178[9,1]	0.70956	0.00001	-12.99	-4.26	26.52	45	unknown	F	BA3
182[9,3]	0.70960	0.00003	-13.19	-3.28	27.53	34	young	F?	BA4
185[9]	0.70961	0.00002	Not enough material for analysis			31	young	M	BA5
188[1,2]	0.70970	0.00001	-13.46	-4.47	26.30	16	young- mid	F	BA4
190[2,3]	0.70990	0.00001	-13.07	-4.81	25.95	27 & 28	young-mid	F	N2
194[1,2]	0.71136	0.00001	-13.63		26.45	unknown	mid	F	N2
196[2,5]	0.70965	0.00002	-12.94	-3.87	26.92	25	young	F	BA3
197[1,5]	0.70964	0.00001	-13.55	-3.05	27.77	38 & 18	mid-old	M	BA2
201[1,2]	0.70970	0.00001	-14.19		26.45	unknown	mid-old	M	BA3
204[9,8]	0.70987	0.00001	-13.32	-3.41	27.40	36	mid	?	IA2
211[9,8]	0.70951	0.00001	-11.63	-3.65	27.15	unknown	mid-old	M?	IA1
223[6]	0.70963	0.00001	Not enough material for analysis			45	old	F	BA4

224[8,6]	0.70958	0.00001	-12.84	-5.54	25.20	35	v young	F	BA4
225[9,8]	0.70957	0.00001	-12.32	-5.07	25.68	18	old	?	IA1
229[9,8]	0.70981	0.00001	12.80	-3.60	27.20	28	young	M?	IA1
230[6,4]	0.70969	0.00002	-13.33	-4.06	26.73	18	unknown	F?	BA3b
233[8,6]	0.70953	0.00001	-12.98	-4.15	26.63	14	unknown	M	BA4
234[7,4]	0.70953	0.00001	-13.79	-3.72	27.07	45	unknown	F	BA4
238[9,8]	0.71003	0.0001	-13.11	-4.79	25.97	44	old	F?	IA1
241[7,7]	0.70960	0.00001	-13.34	-3.34	27.47	17	mid-old	M	BA5
242[3]	0.70978	0.00001	Not enough material for analysis			25	mid	F	N1
244[8,7]	0.70992	0.00001	-12.84	-4.34	26.44	37	unknown	F	BA5
246[6]	Not enough material for analysis		-13.43	-6.58	24.13	42	mid-old	F	BA4
247[9,8]	0.70970	0.00001	-12.30	-2.50	28.33	34	mid	F?	IA1
248[8,4]	0.07094	0.00001	-13.11	-3.93	26.86	14	young	M	BA3
249[4,1]	0.70979	0.00001	-12.79	-4.05	26.73	24	mid-old	F?	N2
250[3,3]	0.70981	0.00002	-12.32	-3.97	26.82	45	old	M	N1
255[5,7]	0.70984	0.00001	-8.18	-4.07	26.72	48	young	M	N1
256[5,7]	0.70963	0.00001	-13.14	-4.19	26.59	36	mid	F	BA3
257[6]	0.70958	0.00001	Not enough material for analysis			15	mid-old	F	BA4
259[9.8]	0.70987	0.00001	-8.19	-3.28	27.57	27	young	F	IA1
260[5,4]	0.70966	0.00001	-13.39	-4.29	26.49	18	mid?	M	BA3
262[5,6]	0.70967	0.00001	-12.84	-4.74	26.03	14	unknown	?	BA3
263[6,5]	0.70977	0.00002	-12.90	-5.01	25.75	32	young-mid	F	BA3
264[3,4]	0.70964	0.00001	-13.47	-4.22	26.56	35	unknown	F	N1
265[6,2]	0.70975	0.00002	-12.96	-3.15	27.67	34	young	M	BA5
270[6,3]	0.70960	0.00003	-13.30	-4.46	26.31	31	mid-old	M?	BA4
272[8]	0.70952	0.00001	Not enough material for analysis			45	young	M?	BA4
275[8,1]	0.70979	0.00001	-13.32	-4.29	26.49	37	young-mid	F	BA4
276[8,6]	0.70960	0.00001	-13.25	-4.24	26.54	38	young	M	BA4

288[6,5]	0.70956	0.00001	-13.12	-4.06	26.72	31	young	F	BA4
290[6]	0.70968	0.00001	Not enough material for analysis			47	mid	M	BA2
291[8,7]	0.70962	0.00001	-12.79	-3.97	26.82	45	old	F?	BA4
292[7,2]	0.71016	0.00001	-8.70	-5.23	25.52	32	unknown	F?	N1
294[4,7]	0.70980	0.00001	-12.50	-4.67	26.09	25	old	F	N2
296[3]	0.70813	0.00001	Not enough material for analysis			unknown	young	M?	NF
304[6,7]	0.70969	0.00001	-11.57	-5.44	25.30	27	mid	M	N2
306[8,6]	0.70968	0.00002	-13.15	-4.26	26.51	32	mid	M	BA4
319[9,8]	0.70976	0.00001	-12.69	-2.99	27.82	25	mid-old	F	IA1
334[9,8]	0.70965	0.00001	-13.13	-4.65	26.12	18	young	F	IA1
390[9,8]	0.70983	0.00001	-10.96	-2.99	27.83	17	mid	M	IA1
408[7]	0.70959	0.00001	Not enough material for analysis			17	unknown	M	BA4
416[6,4]	0.70958	0.00001	-13.26	-3.39	27.42	35	young	F	BA4
430[6,2]	0.70960	0.00001	-13.40	-4.86	25.90	38	young	F	BA4
431[6]	0.70991	0.00001	Not enough material for analysis			18	mid	M?	BA3
438[5]	0.71002	0.00001	Not enough material for analysis			47	mid	M?	NF
439[7,2]	0.70950	0.00001	-13.69	-4.01	26.78	47	unknown	M	BA3
440[6]	0.70813	0.00002	Not enough material for analysis			24	old	F	BA4
443[7,4]	0.70971	0.00001	-13.31	-4.16	26.62	38	unknown	M?	BA3
445[8,7]	0.70952	0.00002	-13.13	-4.41	26.36	48	young	M	BA3
446[8,5]	0.70979	0.00002	-12.13	-4.51	26.26	34	young	M	BA1
449[8,4]	0.70966	0.00001	-13.36	-3.21	27.60	28	young-mid	F	BA4
454[3]	0.70990	0.00001	Not enough material for analysis			unknown	mid-old	F	NF
456[2,1]	0.70971	0.00002	-13.33	-4.32	26.45	24	young?	F	BA2
460[7,2]	0.70965	0.00001	-13.68	-4.42	26.35	12	unknown	F	BA2
461[3,4]	0.70987	0.00001	-8.41	-4.98	25.77	24	mid	F	NF
463[3,7]	0.70957	0.00001	-8.57	-5.10	25.65	34	mid	F?	NF
474[9,8]	0.70981	0.00002	-13.30	-4.09	26.69	38	young	F	IA1

475[9,8]	0.70972	0.00001	-12.99	-4.07	26.71	48	unknown	?	IA1
478[9,8]	0.70973	0.00001	-12.46	-4.40	26.38	24/25	mid-old	F?	IA1
480[9,8]	0.70978	0.00001	-12.78	-3.83	26.97	14	young-mid	M	IA1
507[8,7]	0.70965	0.00001	-13.57	-4.53	26.24	25	young	?	BA5
517[7]	0.70976	0.00001	Not enough material for analysis			35	unknown	F	BA4
522[8]	0.70955	0.00001	Not enough material for analysis			18	young	M?	BA4
529[7,7]	0.70972	0.00001	-12.41	-3.90	26.89	17	unknown	M	BA4
531[9,8]	0.70961	0.00001	-13.08	-5.54	25.20	48	young	F	IA1
542[7,7]	0.70954	0.00001	-12.87	-4.59	26.17	27	unknown	F	BA4
544[7,6]	0.70943	0.00001	-12.97	-5.26	25.49	25	unknown	M?	BA4
549[7,6]	0.70956	0.00001	-13.52	-4.54	26.23	32	unknown	M?	BA4
553[8,7]	0.70975	0.00001	-13.30	-4.52	26.25	46	mid	?	BA2
554[7,6]	0.70951	0.00001	-13.08	-4.06	26.73	32	unknown	F	BA4
555[8,4]	0.70963	0.00001	-13.48	-4.17	26.61	24	young	M	BA2
556[2,6]	0.70991	0.00001	-12.73	-4.27	26.51	24	mid	F?	N2
558[4]	0.70957	0.00001	Not enough material for analysis			14	old	M?	N2
562[2,3]	0.70977	0.00001	-13.23	-4.91	25.85	35	old	M	N2
564[7,1]	0.70944	0.00001	-13.93	-4.78	25.98	24	unknown	M	BA4
566[7,5]	0.70987	0.00001	-12.06	-5.79	24.94	44	mid	M	NF
569[7,6]	0.70987	0.00001	-12.69	-4.14	26.64	17	unknown	F?	BA1
570[7,7]	0.70977	0.00001	-13.61	-3.57	27.23	24	unknown	M	BA2
593[7,7]	0.70959	0.00001	-12.82	-4.40	26.37	14	unknown	unknown	BA3
600[7,7]	0.70958	0.00001	-13.46	-3.47	27.33	17	unknown	F	BA3
609[7,7]	0.70966	0.00001	-13.41	-3.09	27.72	25	unknown	M?	BA3
611[7,7]	0.70971	0.00001	-13.44	-4.42	26.36	47	unknown	M?	BA3
613[8]	0.70954	0.00001	Not enough material for analysis			37	Young	M?	BA4
616[7]	0.70974	0.00001	Not enough material for analysis			37	unknown	M	BA3

618[7,7]	0.70989	0.00001	-12.98	-4.83	25.93	47	unknown	F	BA3
620[8,2]	0.70955	0.00002	-13.24	-3.42	27.38	45	young	F	BA4
624[5,7]	0.70975	0.00001	-13.21	-3.76	27.04	35	mid-old	F	BA3
626[3]	0.70990	0.00001	Not enough material for analysis			15	young	M	NF
631[5,2]	0.70971	0.00001	-13.41	-4.20	26.58	18	mid	M	BA3
632[4]	0.70973	0.00001	Not enough material for analysis			28	young	M?	N2
633[3]	0.70987	0.00001	Not enough material for analysis			35	young	F	NF
Faunal Samples									
F2.6[5]	0.71000	0.00001	-11.76	-7.89	22.78				
F1.6[5]	0.70991	0.00001	-11.77	-7.89	22.78				
F3:1[3]	0.70981	0.00001	-11.93	-4.15	26.63				
F3.9[4]	0.70986	0.00001	-11.95	-3.45	27.35				
F4.14[5]	0.07099	0.00001	-11.94	-3.61	27.19				

Appendix 3 – Mortuary Goods

Table 2: The grave goods found with each of the individuals analysed isotopically during this study. This table is referred to as supplementary table 2 in manuscript 2.

Site	Burial #	shell beads	shell artefacts	ceramic vessels	bronze artefacts
BLK	17	0	2	4	0
	19	0	1	6	0
	21	0	8	0	0
	34	0	7	0	0
	39	0	16	0	0
	42	0	0	4	0
	46	0	0	0	0
	49	0	0	2	0
	51	0	0	0	0
	52	2595	4	4	0
	53	0	5	0	0
	64	0	1	10	0
	75	0	0	4	0
	77	0	1	5	0
	79	0	1	5	0
	28	0	0	2	0
	30	786	0	5	0
	44	3	1	0	0

48	3	0	7	0
65	0	0	1	0
67	0	0	5	0
71	0	0	1	0
82	0	0	5	0
89	150	13	0	0
94	0	0	0	0
109	0	0	4	0

Site	**Burial #**	**shell beads**	**shell artefacts**	**ceramic vessels**	**bronze artefacts**
BNW contemp. to BLK	20	9101	32	82	2
	23	5	0	2	0
	25	1	0	3	0
	26	0	0	4	0
	90	9101	35	82	0
	93	1802	0	34	0
	106	9660	6	51	0
	153	0	0	1	0
	161	7849	57	13	0
	178	1180	49	29	1
	190	0	0	2	0
	194	0	0	2	0
	196	5902	21	26	0

201	619	86	12	5
230	0	0	7	0
248	85	0	13	0
256	4875	20	20	0
260	1425	217	24	0
262	23682	68	30	1
294	0	0	1	0
304	0	0	0	0
439	21	14	17	0
443	1632	24	25	0
445	430	49	26	2
446	100	1	11	1
456	6173	1	21	0
460	1105	2	34	0
460	1105	2	34	0
553	900	4	42	1
556	0	1	0	0
562	0	0	1	0
569	2382	5	14	1
570	3407	0	18	0
600	10	1	7	0
611	0	0	7	0
618	0	2	12	0
624	12691	8	34	0
631	567	47	14	0

	burial #	shell artefacts	glass beads	ceramics	metal objects
NUL	1	0	0	3	77
	4	0	1	2	7
	5	0	2	0	2
	8	0	10	2	2
	10	0	1	0	17
	12	0	0	2	15
	15	0	1	1	0
	16	0	1	1	3
	30	0	1	0	15
	33	0	0	0	1
	35	0	1	0	22
	36	0	0	0	3
	39	0	1	0	6
	40	0	1	0	6
	42	42	0	1	0
	44	0	0	0	0
	48	0	2	0	5
	50	0	1	0	0
	62	0	3	3	106
	66	0	0	0	0
	67	1	0	0	3
	68	0	0	3	56
	69	0	1	4	190
	74	0	1	3	3

	86	0	2	2	6
	94	0	3	0	4
	104	0	2	3	3
	110	1	5	1	1
	111	0	0	1	9
	113	0	1	4	185
	burial #	**shell artefacts**	**glass beads**	**ceramics**	**metal objects**
BNWContemp. to NUL	36.1	0	12	3	2
	36.2	0	12	3	2
	119	0	0	0	13
	204	0	0	0	0
	211	0	0	9	3
	225	0	0	3	0
	229	1	0	8	8
	238	0	0	1	0
	247	0	0	1	0
	259	0	3	4	0
	319	1	0	3	0
	334	0	0	0	0
	390	1	0	6	6
	474	1	0	2	0
	475	0	0	6	0
	478	7	0	15	0

480	0	0	7	5
482	0	0	9	2
531	0	0	4	0

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O dry bones, hear the word of the Lord…Behold, I will cause breath to enter you, and you shall live.